Development of a Coal Quality Expert

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DISCLAIMERS

ABSTRACT

ABB Power Plant Laboratories Combustion Engineering, Inc., (ABB CE) and CQ Inc. completed a broad, comprehensive program to demonstrate the economic and environmental benefits of using higher quality U.S. coals for electrical power generation and developed state-of-the-art user-friendly software--Coal Quality Expert (CQE)--to reliably predict/estimate these benefits in a consistent manner. The program was an essential extension and integration of R&D projects performed in the past under U.S. DOE and EPRI sponsorship and it expanded the available database of coal quality and power plant performance information. This software will permit utilities to purchase the lowest cost clean coals tailored to their specific requirements.

Based on common interest and mutual benefit, the subject program was cosponsored by the U.S. DOE, EPRI, and eight U.S. coal-burning utilities. In addition to cosponsoring this program, EPRI contributed its background research, data, and computer models, and managed some other supporting contracts under the terms of a project agreement established between CQ Inc. and EPRI. The essential work of the proposed project was performed under separate contracts to CQ Inc. by Electric Power Technologies (EPT), Black & Veatch (B&V), ABB Combustion Engineering, Babcock & Wilcox (B&W), and Decision Focus, Inc.

Although a significant quantity of the coals mined in the United States are now cleaned to some degree before firing, for many of these coals the residual sulfur content requires users to install expensive sulfur removal systems and the residual ash causes boilers to operate inefficiently and to require frequent maintenance. Disposal of the large quantities of slag and ash at utility plant sites can also be problematic and expensive. Improved and advanced coal cleaning processes can reduce the sulfur content of many coals to levels conforming to environmental standards without requiring post-combustion desulfurization systems. Also, some coals may be beneficiated or blended to a quality level where significantly less costly desulfurization systems are needed. Coal cleaning processes may also be used to remove the precursors of other troublesome emissions that can be identified now or in the future.

An added benefit of coal cleaning and blending is the reduction in concentrations of mineral impurities in the fuel leading to improved performance and operation of the boiler in which it is fired. The ash removed during the pre-combustion cleaning process can be more easily and safely disposed of at the mine than at the utility plant after combustion. EPRI's Coal Quality Impact Model (CQIM) has shown that improved fuel quality can result in savings in unit capital and operating costs. This project produced new and improved software to select coal types and specifications resulting in the best quality and lowest cost fuel to meet specific environmental requirements.

During the program, 13 coal samples and one petroleum coke were tested to evaluate their raw fuel characteristics, mineral liberation potential, and trace elements contents. Washability tests were conducted on the raw coals to determine their potential for beneficiation. From the initial group, four coals were beneficiated to two levels (one "medium" and one "deep" cleaned) in CQ Inc.'s Coal Quality Development Center (CQDC) at Homer City, Pennsylvania. Samples of the coals produced at the CQDC and in commercial coal cleaning plants, as appropriate, were provided to ABB-CE and B&W for testing in the laboratory and in small (4-5 MBtu/hr) test rigs. ABB-CE evaluated the combustion effects of seven samples for tangentially-fired combustion systems and B&W performed a similar evaluation of two samples for cyclone combustors. Field testing in 200-900 MW coal-fired utility boilers was done at six power plant sites. A total of 13 tests were coordinated by EPT and the data were used to validate CQIM, developed for EPRI by B&V, and to develop new capabilities to supplement CQIM and produce the Coal Quality Expert (CQE).

CQE predicts the performance of various commercially available coals with regard to site-specific total plant performance, i.e., pulverization characteristics (mill wear, energy requirements), combustion performance (ignition stability, carbon burnout), fireside performance (slagging, fouling, ash erosion), and emissions (particulate, SO_2, NO_x). CQE combines results from the precedent CQIM with EPRI's Coal Cleaning Cost Model, NO_x formation model, precipitator model, and a coal transportation model to perform cost benefit analyses of improved coal quality on power plant performance.

The work effort started on May 3, 1990 and was completed on June 30, 1996, in accordance with the intent of the Clean Coal Institute (Public Law 99-29b), as a broad-based technology demonstration that will be useful to all coal-firing U.S. utilities.

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Project Participants
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Host Utilities - Full-scale Power Plant Tests
- Brayton Point, Unit 2 (250 MW), Somerset, MA, New England Power Company
- Brayton Point, Unit 3 (620 MW), Somerset, MA, New England Power Company
- Gaston, Unit 5 (880 MW), Wilsonville, AL, Alabama Power Company
- King (560 MW), Oak Park, MN, Northern States Power
- Northeastern, Unit 4 (445 MW), Oologah, OK, Public Service of Oklahoma
- Watson, Unit 4 (250 MW), Gulfport, MS, Mississippi Power Company

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Memorial

From May 1990 through September 8, 1994, Mr. Robert J. Evans served as DOE's technical representative and project manager for the CQE project. As he did on all of his DOE Clean Coal Technology projects, Bob actively participated in the technical, business, financial, and teamwork aspects of this project. His technical training and experience resulted in insightful questions and suggestions regarding the specification and operation of the CQE software. His experience and perspectives provided guidance to our marketing and business planning efforts and his reviews of project finances served as watchful reminders during the course of the project. Most importantly, Bob's honesty, ethics, and principles were admired by everyone he met.

With an appropriate balance of humility and conviction Bob challenged the project participants to do their best in achieving the project's and product's objectives. He treated everyone with honesty, respect, and friendship, and he did not compromise his integrity. As a man of such integrity and compassion, Bob Evans should be remembered always.

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
ABB CE	ABB Power Plant Laboratories Combustion Engineering, Inc.
AL	Alabama
Al	aluminum
Al_2O_3	aluminum oxide (oxide of an element in ash)
APC	Alabama Power Company
ARA	Acid Rain Advisor
ASTM	American Society for Testing and Materials
AT	air table
AZ	Arizona
Btu	British thermal unit(s)
B&V	Black & Veatch
B&W	Babcock & Wilcox, Inc.
C	carbon
cc	clean coal
c	prefix centi- (10^{-2} or hundredth)
°C	Celsius degrees (temperature)
Ca	calcium
CaO	calcium oxide (oxide of an element in ash)
CCSEM	computer-controlled scanning electron microscopy
Cl	chlorine (a trace element in coal)
CO	Colorado
CPU	central processing unit (computer term)
CQDC	Coal Quality Development Center
CQE	Coal Quality Expert
CQIM	Coal Quality Impact Model
CQIS	Coal Quality Information System (an EPRI data base)
CT	concentrating table
cum	cumulative
d.b.	dry basis
DOE	United States Department of Energy
DTFS	Drop Tube Furnace System
EER	Energy and Environmental Research Corporation
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
EPT	Electric Power Technologies, Inc.
ESP	Electrostatic Precipitator

F	fluorine (a trace element in coal)
°F	Fahrenheit degrees (temperature)
F/S	float/sink
Fe	iron
FEGT	furnace exit gas temperature
FPTP	Fireside Performance Test Facility
Fe_2O_3	ferric oxide (oxide of an element in ash)
FERCO	Fossil Energy Research Company
FeS_2	pyrite, a mineral containing sulfur
FF	froth flotation
GA	Georgia
H	hydrogen
H_2O	water
HGI	Hardgrove Grindability Index per ASTM D-409
HMC	heavy-media cyclone
HMV	heavy-media vessel
IBM	International Business Machines Corporation
i.e.,	that is
IL	Illinois
IN	Indiana
in	inch(es)
inc	incremental
k	prefix kilo- (10^3 or thousands, except for computers where K=1,024)
K	potassium
K_2O	potassium oxide (oxide of an element in ash)
KS	Kansas
KY	Kentucky
lb	pound(s)
lb/MBtu	pound(s) per million British thermal units
LOI	loss on ignition
M	prefix mega- (10^6 or millions)
M	Tyler mesh as in 28M
m	prefix milli- (10^{-3} or millionth)
MAF	moisture-ash-free
MBtu	millions of British thermal unit(s)
MD	Maryland
Mg	magnesium
MgO	magnesium oxide (oxide of an element in ash)
mm	millimeter(s)
MN	Minnesota

Mn	manganese
MnO_2	manganese dioxide (oxide of an element in ash)
MO	Missouri
MPC	Mississippi Power Company
MT	Montana
MW	megawatt(s)
N/A	not applicable
N/R	not reported
N	nitrogen
Na	sodium
Na_2O	sodium oxide (oxide of an element in ash)
NEP	New England Power Company
NM	New Mexico
No.	number
NO_x	nitrogen oxide(s)
NSP	Northern States Power Company
NSPS	new source performance standards
O	oxygen
OH	Ohio
OK	Oklahoma
P	phosphorus
P_2O_5	phosphorus pentoxide (oxide of an element in ash)
PA	Pennsylvania
PC	personal computer
PETC	Pittsburgh Energy Technology Center
PSIT	Physical Sciences Incorporated Technology Company
PSO	Public Service Company of Oklahoma
R&D	research and development
RAM	random access memory (computer term)
ref.	refuse
ROM	run-of-mine
R_f	fouling index (eastern-type ash)
R_f'	fouling index (lignitic-type ash)
R_s	slagging index (eastern-type ash)
R_s'	slagging index (lignitic-type ash)
S	sulfur
SBS	Small Boiler Simulator
SCS	Southern Company Services
SEMPC	scanning electron microscopy point count
SG	separating specific gravity
Si	silicon
SiO_2	silicon dioxide (oxide of an element in ash)

SO_2	sulfur dioxide
SO_3	sulfur trioxide
SoRI	Southern Research Institute
Sp Gr	specific gravity
Ti	titanium
TiO_2	titanium dioxide (oxide of an element in ash)
TN	Tennessee
TX	Texas
UNDEERC	University of North Dakota Energy and Environmental Research Center
USBM	United States Bureau of Mines
UT	Utah
VA	Virginia
W	watt(s)
WA	Washington
WOC	water-only cyclone
2-WOC	two-stage, middlings-recirculation, water-only cyclones
WOC-2	two-stage, water-only cyclones
Wt	weight
WV	West Virginia
WY	Wyoming
%	percent
-28M	smaller than 28M
+28M	larger than 28M
28M x 48M	28M by 48M size fraction
1.40 x 1.50	1.40 by 1.50 specific gravity fraction

GLOSSARY

Ash Association - The physical and chemical methods in which ash forming minerals and other inorganic substances are affiliated with coal:

- Free (or liberated) ash) - a particle comprised of predominantly mineral matter. CQ Inc. loosely defines a particle to be free ash if its mean specific gravity is greater than or equal to 2.0. Free ash (or more properly the mineral matter that produces ash when the coal is burned) is the portion of a coal's impurities most easily removed by physical coal cleaning.

- Entrained ash - is physically, though not chemically, bound with coal. Particles with entrained mineral matter are referred to as "locked particles." For some coals, additional size reduction can preferentially break the entrained mineral matter away from the coal particles.

- Intrinsic ash - refers to mineral matter chemically bound in coal particles. The minerals are part of the carbon containing molecules making up the coal.

- Inherent ash - includes both ash from entrained mineral matter and other inorganic matter intrinsic in the coal molecules. Inherent ash matter can not be removed by physical coal cleaning.

Ash Type - determined by comparing the sum of calcium (CaO) and magnesium (MgO) oxides with the quantity of iron oxide (Fe_2O_3). If CaO + MgO is greater than Fe_2O_3 the ash is defined as lignitic type ash (western-type coal). If Fe_2O_3 is greater than CaO + MgO the ash is defined as a bituminous-type ash (eastern-type coal). This criterion applies to all coal ranks regardless of source. Thus, a Colorado anthracite could have a lignitic-type ash and a Texas lignite could have a bituminous ash.

As-received Sample - a sample in the state in which it was received. Generally used to denote that all determinations presented are based on the moisture level of a coal sample when received by the laboratory performing the analysis.

Dry Ash - data calculated to a theoretical base of no moisture associated with the sample.

Clean Coal - the product of a coal cleaning process that has been improved in quality by removal of mineral matter from raw coal. Improved quality generally means a decrease in ash and/or sulfur and an increase in the heating value of the coal.

Combustibles - the weight proportion of raw coal, clean coal or refuse that burns when the material is ashed using ASTM's D 3174 procedure. Combustibles are calculated using the following equation:

Combustibles = 100 - Dry Ash Value

where both combustibles and ash are dry weight percents (Wt %).

Continuous Mining - a system of underground mining which employs a mining machine capable of cutting the coal from an exposed face in a nearly uninterrupted manner.

Conventional Mining - a system of underground mining which entails making a relief cut, drilling the face to permit insertion of explosives, blasting the coal, and removing the coal from the mine.

Deep-Mined Coal (Underground Mining) - coal which is mined from deposits covered by sedimentary deposits of soil, rock and the like. Access to this coal is obtained by leaving the overburden in place, rather than by removing the overburden, as in surface or strip mining.

Float/Sink - a laboratory procedure where coal is placed in organic liquids of preselected specific gravities beginning at the lowest. The float material is then weighed and the sink material is tested in the next higher gravity bath.

Flowsheet - a schematic drawing showing the various operations of a process. A configuration of units is also referred to as a flowsheet.

Fouling - the accumulation of deposits on heat exchange surfaces in the convection pass section of a steam generator.

Fouling Index (Factor) - a parameter (R_f or R'_f) empirically developed to relate chemical tests performed on small scale laboratory samples of coal to the tendency of alkali bonded deposits to form on steam generator convection surfaces.

Grindability Index (HGI) - grindability is a term used to measure the ease of pulverizing a coal - ASTM standard D409 describe a method of testing to measure the Hardgrove Grindability Index (HGI). Coals with an HGI or 100 are very easy to grind and coals with lower numbers are progressively harder to grind. Typical results range from 40 to 120.

Head Split - a representative portion of a sample taken for analysis before the remaining portions are separated into size and/or specific gravity fraction. Taken off the top (not literally) or taken first.

Liberation - the process of breaking raw coal into particles that are predominately either valuable coal or undesirable impurities such as ash and sulfur. Some particles are too high in impurities or too low in valuable coal to be classified impurity or coal; thus, these particles are referred to as locked particles. CQ Inc. classifies a particle to have impurities liberated if its density is greater than or equal to 2.0 specific gravity unless some other transition gravity is cited.

Longwall - an underground mining strategy in which coal is removed from a longwall (face) of coal in the deposit in a series of parallel cuts on the face. The length of the cut may be from 500 to 1000 feet, hence the term, longwall.

Mesh - the number of openings per linear inch, counting from the center wire. Refers to both the screen size and the particle size that passes through a given mesh screen or sieve. CQ Inc. uses Tyler Standard Mesh designations unless stated otherwise.

Moisture - a general term referring to the types of water associated with the coal particles. Surface moisture generally refers to the moisture that can be readily removed and includes interparticle water, adhesion water and part of the capillary water. Inherent moisture generally refers to water that is more difficult to remove (other than by extensive thermal drying) and includes interior and surface adsorption water and part of the capillary water.

Oversize - material retained on a screen (or sieve) or that is discharged from the deck of a vibrating screen without passing through the screen openings.

Raw Coal (R.C.) - once the run-of-mine coal has been treated by removing tramp iron, screening or crushing the material is referred to as raw coal.

Recovery - the portion of a desirable part of coal that is extracted by a separation process as the valuable (clean coal) product. Common uses are heating-value recovery and combustibles recovery. Recovery is calculated by the following equation:

$$\textit{Desirables Recovery} = \frac{\textit{Yield x Clean-Coal Value}}{100 \textit{ x Raw-Coal Value}} \textit{ x } 100$$

where the desirables values are expressed as either weight percents or energy units and the desirables recovery units are percent of the raw-coal amount (Wt % or just % for heating-value recovery).

Reduction - the percentage change in the amount of some undesirable constituent of coal caused by cleaning the coal. Common uses are for SO_2 reduction, ash reduction, and sulfur reduction. Reduction is calculated with the following equation:

$$Impurity\ Reduction = \frac{(Raw\text{-}Coal\ Value)\ -\ (Clean\text{-}Coal\ Value)}{(Raw\text{-}Coal\ Value)}\ x\ 100$$

where the impurity value is expressed in lb/MBtu and the impurity reduction is expressed as a percentage change (%) from the raw coal's value.

Refuse - the undesirable mineral matter impurities (usually high in ash or sulfur) contained in raw coal and rejected by the cleaning plant in producing an improved clean coal product. Usually composed of rock, slate, shale, bone, pyrite, and other minerals.

Reject - a general term referring to unwanted material.

Removal - the percentage of some raw-coal impurity's weight extracted as refuse by a coal-cleaning process. Common uses are for ash removal and sulfur removal. Removal is calculated with the following equation:

$$Impurity\ Removal = \frac{(100\ -\ Yield)\ x\ Refuse\ Value}{100\ x\ Raw\text{-}Coal\ Value}\ x\ 100$$

where the impurity value is expressed as the weight percent of the impurity in the stream and the yield is the proportion of the total raw coal's weight extracted as clean coal. Impurity removal's units are weight percent (Wt %).

Run-of-Mine (ROM) - designates the product from the mining process prior to any type of treatment. In deep mining face crushers are considered part of the mining operation and coal coming from them is still run-of-mine coal.

Screening - the process by which coal is separated into different size fractions. Size smaller than the screen opening pass through and larger sizes are retained on the screen.

Size - the size of a particle is defined in terms of a surface opening through which the particle will pass. The openings are stated in terms of the square opening dimension in inches for the larger sizes and in terms of the Tyler mesh screens for smaller particle sizes.

Slagging - the accumulation of molten or "tacky" deposits on heat exchange surfaces in the radiant heat sections of a steam generator.

Slagging Index (Factor) - a parameter (R_s) empirically developed to relate ASTM-type analyses of coal ash to fused slag deposits.

SO_3 Free - is used with low-rank coals. Low-rank coals are high in carbonates (calcite) and sulfur retained as sulfates may be both unduly high and nonuniform between duplicate samples. In such cases sulfate sulfur (SO_3) in the ash can be determined by ASTM method D1757 and the ash values corrected.

Strip-mined Coal (Surface Mining) - a mining strategy in which the overburden (earth cover) is removed by draglines, bulldozers, front-end loaders or power shovels to gain access to the coal. The overburden is replaced after coal removal.

Topsize - ASTM D431 defines the topsize of a material quantity as the smallest sieve (or screen opening) upon which is retained a total of less than five percent of the sample.

Yield - the proportion of the total coal material (usually its weight but can be its volume if explicitly stated) that enters a separating process and is extracted as the desirable or clean-coal product. Yield is used exclusively for the total coal material; when expressing the extraction of portions of the total coal's material, the terms recovery or removal are used. Yield's units are Wt % or Vol %.

EXECUTIVE SUMMARY

The U.S. Department of Energy's Clean Coal Technology (CCT) Program was established to accelerate the commercialization of new technologies for reducing acid rain precursors--SO_2 and NO_x. Technologies that also improve the efficiency of power generation provide the added benefits of increasing U.S. competitiveness and reducing emissions of other combustion by-products, such as CO_2 and trace elements that have been identified as potential air toxics. CQ Inc. and ABB Power Plant Laboratories Combustion Engineering, Inc., with co-funding from the Electric Power Research Institute (EPRI), were awarded a project under the first round of the CCT program.

Technology Description

The Coal Quality Expert (CQE™) project addressed fuel quality from the coal mine to the busbar and the stack while integrating and improving several predecessor software tools, including:

- EPRI's Coal Quality Information System
- EPRI's Coal Cleaning Cost Model
- EPRI's Coal Quality Impact Model
- EPRI's NO_x Formation Model
- EPRI and DOE models to predict slagging and fouling

CQE, the software product developed during this project, can be used as a stand-alone workstation or as a network application by utilities, coal producers, and equipment manufacturers to perform detailed analyses of the impacts of coal quality, capital improvements, operational changes, and/or environmental compliance alternatives on power plant emissions, performance, and production costs.

Demonstration Program

ABB CE and CQ Inc. were joined by several subcontractors and project participants to perform the demonstration program that featured coal characterizations, pilot-scale combustion tests, and boiler field tests at host utility sites. These tests provided data for algorithm and model development and validation. The subcontractors and project participants included:

- Black & Veatch, Overland Park, KS
- Babcock & Wilcox, Alliance, OH
- Electric Power Technologies, Menlo Park, CA
- GUILD Products, Inc. (formerly Expert-EASE), Belmont, CA
- Decision Focus, Mountain View, CA
- Karta Technologies, San Antonio, TX

- University of North Dakota, Grand Forks, ND
- PSI Technology, Andover, MA
- Energy & Environmental Research Corporation, Irvine, CA
- Southern Company Services, Birmingham, AL
- Fossil Energy Research Corp., Laguna Hills, CA
- Southern Research Institute, Birmingham, AL

The scope of this test work is outlined in Table S-1.

Table S-1
CQE Work Scope

Test Sites	ABB CE	B&W	B&V	CQ Inc.	UNDEERC	EPT	GUILD
Public Service OK Northeastern Station	5 DTFS 5 FPTF	NA	need FT/PT/BT data	2 CCC	4 DTFS 5 SEM	3 FT	NA
Mississippi Power Company Watson Station	2 DTFS 2 FPTF	NA	need FT/PT/BT data	4 CCC	2 DTFS 2 SEM	2 FT	NA
Northern States Power King Station	NA	2 SBS	need FT/PT/BT data	5 CCC	2 SEM	2 FT	NA
Alabama Power Company Gaston Station	1 DTFS 1 FPTF	NA	need FT/PT/BT data	2 CCC	NA	2 FT	NA
New England Power Brayton Point	NA	NA	need FT data	NA	NA	2 FT	NA
New England Power Brayton Point	NA	NA	need FT data	NA	NA	2 FT	NA
Other CQE Work	commercial applications	NA	CQE software developer, CQIM enhancements, ARA	Coal Cleaning Cost Model, CQIS enhancements, select CQE test sites	ash deposition data & model inputs	Fireside Testing Guidelines	develop CQE shell specs

CCC--Coal Cleanability Characterization
SBS--Small Boiler Simulator (Pilot Test)
BT--Bench Test
DTFS--Drop Tube Furnace System
FT--Field Test
PT--Pilot Test
FPTF--Fireside Performance Test Facility (Pilot Test)
SEM--Scanning Electron Microscopy
NA - Not Applicable

Coal Characterizations

Between 1990 and 1992, CQ Inc. engineers conducted detailed coal cleanability characterizations for thirteen coals to provide baseline coal data for CQE. These characterizations involved investigations of physical and chemical properties of all components of the coal and assessments of the theoretical potential for removing ash-forming, sulfur-bearing, and trace element-bearing minerals associated with the coal. In addition, many of the characterizations included commercial-scale cleaning evaluations to examine the practical extent to which coal quality may be improved using various coal cleaning techniques.

The coal characterization for the APC Gaston Station gives a comprehensive example of a coal characterization and the use of coal cleaning for ash, sulfur, and trace element removal. Pratt and Utley seam coals from Pittsburg and Midway Coal Mining Company's North River No. 1 and Meg No. 5 mines, respectively, were evaluated. Raw coal analyses for each coal are given in Table S-2.

The washability analysis conducted for the Pratt Seam coal is presented graphically in Figure S-1 in conjunction with data from the liberation study. The liberation study involved crushing each of the coals to determine if size reduction can improve the liberation of minerals from coal, allowing the minerals to be removed to a greater extent than in the raw coal. Figure S-1 shows that both these coals can be improved using coal cleaning techniques. For example, crushing and cleaning operations can reduce the ash content of Pratt Seam coal by over 65 percent while achieving 90 to 95 percent energy recovery. The data in the figure also shows that intense cleaning, including crushing to a topsize of at least minus 100 mesh, will likely be required to produce clean coal having SO_2 emissions levels of 2.5 lb/MBtu or less. The cleaning and liberation potentials from Utley seam are similar.

To evaluate the effectiveness of coal cleaning on Pratt and Utley seam coals, project engineers completed four flowsheet tests: one with the CQDC standard heavy-media cyclone/water-only cyclone/froth flotation flowsheet, two with a concentrating table flowsheet, and one with a concentrating table/spiral concentrator flowsheet. The standard flowsheet was used to represent an intense cleaning application, while the concentrating table flowsheets were used to represent low-cost cleaning options either with or without a specific circuit for removing sulfur-bearing pyrite. A summary of results for all flowsheet tests is given in Tables S-3 and S-4.

Raw coal feed for all tests was crushed to minus 3/8-inch top-size. The circulating specific gravity for the heavy-media cyclone circuit in Flowsheet 1 was 1.60. No attempt was made to clean or recover nominal -100 mesh coal in either Flowsheet 2 or 3.

As shown in Table S-3, clean coal yield from these four flowsheet tests ranged from 52 to 72 percent. Only cleaning in Flowsheet 1 produced an energy recovery exceeding 86 percent. A comparison of the responses of Pratt Seam (Test 2) and

Table S-2
Raw Coal Quality Summary for Pratt and Utley Seam Coals (Dry basis analyses except where noted)

	Pratt Seam Fayette County, AL	Utley Seam Tuscaloosa County, AL
Total Moisture (As-received) (Wt %)	6.64	6.71
Fixed Carbon (Wt %)	42.63	48.35
Volatile Matter (Wt %)	31.51	36.38
Ash (Wt %)	25.86	15.27
Higher Heating Value (Btu/lb)	10,777	12,594
Total Sulfur (Wt %)	2.13	3.81
Pyritic Sulfur (Wt %)	1.10	2.16
Organic Sulfur (Wt %)	1.01	1.42
SO_2 Emission Potential (lbs/MBtu)	3.95	6.04
Carbon (Wt %)	59.55	68.19
Hydrogen (Wt %)	4.89	4.86
Nitrogen (Wt %)	1.36	1.27
Oxygen (Wt %)	6.71	6.60
Chlorine (Wt %)	0.08	0.05
Grindability (HGI)	62	66
Ash Fusibility (Reducing/Oxidizing)		
Initial Deformation (°F)	2450/2580	1995/2440
Softening (°F)	2505/2610	2080/2490
Hemispherical (°F)	2550/2665	2200/2515
Fluid (°F)	2605/2710	2315/2540
Slagging Index (Classification)	0.54 (Low)	1.88 (Medium)
Fouling Index (Classification)	0.13 (Low)	0.12 (Low)

Slagging Index Classification		Fouling Index Classification	
Low	< 0.6	Low	< 0.2
Medium	0.6 to 2.0	Medium	0.2 to 0.5
High	2.0 to 2.6	High	0.5 to 1.0
Severe	> 2.6	Severe	> 1.0

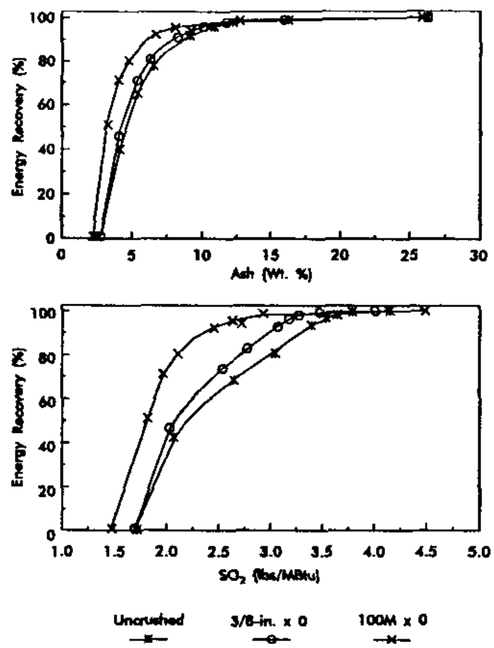


Figure S-1
Potential Ash and SO_2 Reduction of Uncrushed and Crushed Pratt Seam Coal

Utley Seam (Test 3) coals to cleaning by the same flowsheet shows that ash reduction was markedly higher for Pratt Seam coal than for Utley Seam coal, but that the reductions of sulfur dioxide precursors were similar. Cleaning results from Test 4 show that the addition of a spiral concentrator circuit to the table flowsheet did not improve the removal of pyrite from Pratt Seam coal significantly, but the use of this intermediate-size coal cleaning circuit did help to reduce the ash content of the clean coal by another three percentage points.

As indicated by the data in Table S-4, concentrating table-based flowsheets reduced the calcareous and siliceous mineral matter content of both the Pratt and Utley seam coals adequately. However, these flowsheets did not reduce the alumina and aluminosilicate contents as well as did Flowsheet 1.

Unfortunately, in the case of the Pratt Seam coal, the use of coal cleaning appears to have exacerbated some of its combustion problems. Coal cleaning decreased the ash fusion temperatures of the Pratt Seam coal and increased its slagging and fouling potentials. This is probably the result of the inability of these flowsheets to remove iron oxide- and alkali metal-bearing minerals as readily as other ash-forming mineral matter. In addition, cleaning in Flowsheet 1 increased the chlorine concentration of the Pratt/Utley blend over two-fold. For the most part, the ash composition and fusibility of Utley Seam coal was unaffected by cleaning, even though substantial amounts of mineral matter were removed.

Table S-3
Flowsheet Performance Comparison: Pratt and Utley Seam Coals, Alabama

	Test 1 90% Pratt/10% Utley Blend HMC/WOC/FF		Test 3 Utley Seam CONC. TABLE	
ANALYSES	RAW COAL	CLEAN COAL	RAW COAL	CLEAN COAL
Ash (Wt %)	24.3	7.6	15.7	9.6
Total Sulfur (Wt %)	2.48	2.29	3.65	2.80
Pyritic Sulfur (Wt %)	1.43	1.27	2.46	1.02
Pyritic Sulfur/Total Sulfur (%)	57.6	55.4	67.4	36.4
Higher Heating Value (Btu/lb)	11,121	13,872	12,578	13,570
Ash Loading (lbs/MBtu)	21.8	5.5	12.5	7.0
SO_2 Emission Potential (lbs/MBtu)	4.46	3.30	5.80	4.13
PERFORMANCE				
Yield (Wt %)	NA	72	NA	58
Energy Recovery (%)	NA	89	NA	63
Ash Reduction (Heat Unit Basis, %)	NA	75	NA	43
SO_2 Reduction (Heat Unit Basis, %)	NA	26	NA	34

	Test 2 Pratt Seam CONC. TABLE		Test 4 Pratt Seam TABLE/SPIRAL	
ANALYSES	RAW COAL	CLEAN COAL	RAW COAL	CLEAN COAL
Ash (Wt %)	28.0	11.9	27.3	8.7
Total Sulfur (Wt %)	2.21	2.13	2.33	2.23
Pyritic Sulfur (Wt %)	1.24	1.05	1.49	1.35
Pyritic Sulfur/Total Sulfur (%)	56.1	49.3	63.9	60.5
Higher Heating Value (Btu/lb)	10,582	13,050	10,686	13,717
Ash Loading (lbs/MBtu)	26.5	9.1	25.5	6.3
SO_2 Emission Potential (lbs/MBtu)	4.18	3.26	4.36	3.25
PERFORMANCE				
Yield (Wt %)	NA	52	NA	58
Energy Recovery (%)	NA	64	NA	73
Ash Reduction (Heat Unit Basis, %)	NA	65	NA	75
SO_2 Reduction (Heat Unit Basis, %)	NA	37	NA	42

HMC = Heavy-media Cyclone; WOC = 2-Stage Water-only Cyclone; FF = Froth Flotation
Conc. Table = Concentrating Table; Spiral = Spiral Concentrator; NA = Not Applicable

Table S-4
Clean Coal Combustion Parameters Comparison: Pratt and Utley Seam Coals, Alabama (Dry Basis, except HGI)

	Test 1 90% Pratt/10% Utley Blend HMC/WOC/FF	Test 2 Pratt Seam CONC. TABLE	Test 3 Utley Seam CONC. TABLE	Test 4 Pratt Seam TABLE/SPIRAL
ULTIMATE ANALYSIS				
Carbon (Wt %)	76.1	72.0	73.7	75.0
Hydrogen (Wt %)	5.3	5.1	5.3	5.3
Nitrogen (Wt %)	1.7	1.4	1.5	1.7
Oxygen (Wt %)	6.9	7.5	7.1	7.1
CHLORINE (Wt %)	0.17	0.04	0.03	0.07
GRINDABILITY (HGI)	49	50	53	49
ASH FUSIBILITY (°F) (Reducing/Oxidizing)				
Initial Deformation	2080/2495	2160/2460	1995/2475	2175/2510
Softening	2175/2520	2225/2500	2100/2505	2250/2540
Hemispherical	2270/2535	2320/2535	2225/2525	2330/2575
Fluid	2350/2550	2410/2575	2365/2555	2400/2590
CALCULATED INDICES				
Silica Percentage	0.52	0.62	0.53	0.60
Base-to-Acid Ratio	0.53	0.39	0.58	0.41
Slagging Index (Classification)	1.2 (Medium)	0.8 (Medium)	1.6 (Medium)	0.9 (Medium)
Fouling Index (Classification)	0.28 (Medium)	0.16 (Low-Medium)	0.20 (Low-Medium)	0.16 (Low-Medium)

HMC = Heavy-media Cyclone
Conc. Table = Concentrating Table
WOC = 2-Stage Water-only Cyclone
Spiral = Spiral Concentrator
FF = Froth Flotation

Slagging Index Classification

Low	< 0.6
Medium	0.6 to 2.0
High	2.0 to 2.6
Severe	> 2.6

Fouling Index Classification

Low	< 0.2
Medium	0.2 to 0.5
High	0.5 to 1.0
Severe	> 1.0

In addition to removing ash-forming and sulfur-bearing minerals, cleaning reduced the concentrations of many trace elements found in the Pratt and Utley seam coals. Figure S-2 shows that, irrespective of flowsheet design, cleaning reduced the trace element content of Pratt Seam coal more than did cleaning of Utley Seam coal. Cleaning reduced the concentrations of elements that are associated with ash-forming minerals (barium, chromium, fluorine, lead, nickel, and zinc) more than those of other elements; concentrations are reported in parts-per-million (ppm) on a total coal basis. The results also indicate that equipment selection, configuration (flowsheet design), and their method of operation affect the relative removal of trace elements from these coals.

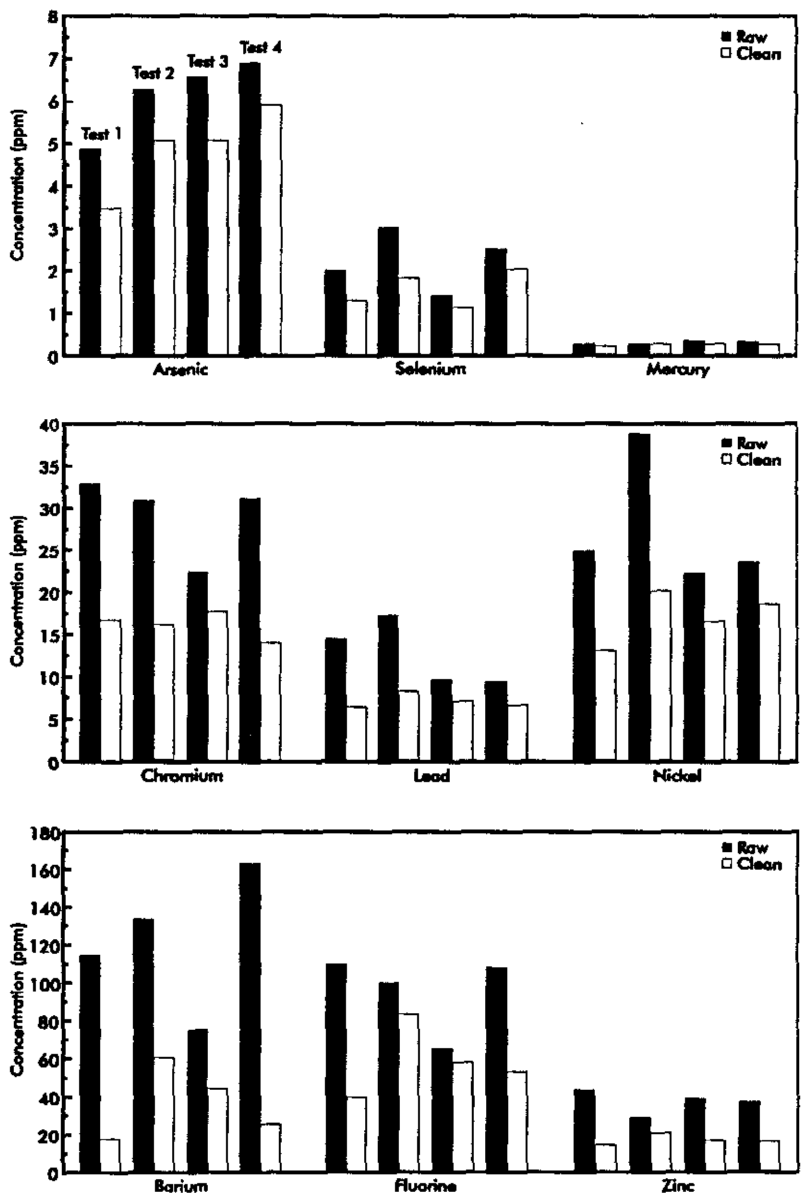


Figure S-2
Trace Element Concentrations in Pratt and Utley Seam Coals: Raw and Clean Coal Analyses by Flowsheet Test

Pilot-Scale Combustion Tests

Pilot-scale combustion tests were conducted to support the coal cleanability characterization and field testing efforts. ABB CE was responsible for all pilot-scale combustion tests, with the exception of the cyclone boiler simulations, which were the responsibility of Babcock & Wilcox (B&W). Bench-scale tests were also conducted by ABB CE, B&W, and the University of North Dakota Energy and Environmental Research Company (UNDEERC) under the general direction of ABB CE. The testing is outlined in Table S-5.

Table S-5
Pilot and Bench-Scale Combustion Test Program

Power Plant	Coal	Sulfur Content	Pilot Test	Bench Test
Northeastern	100 WY	Low	X	X
	100 OK	Low	X	X
	90 WY/10 OK	Low	X	X
	70 WY/30 OK	Low	X	X
	70 WY/30 OK (cleaned)	Low	X	X
Watson	Baseline (IL)	High	X	X
	Alternate (KY)	High	X	X
King	Baseline (70 WY/20 MT/10 Pet Coke)	Low	X	X
	Alternate (93 WY/7 Pet Coke)	Low	X	X
Gaston	Baseline (AL)	High	X	X
	Alternate (WV)	Low		X
Brayton Point 3	Baseline (WV)	Medium		
	Alternate (WV)	Low		X
Brayton Point 2	Baseline (WV)	Low		
	Alternate (KY)	Low		X

Bench-scale testing provided detailed fuel property data for correlation with performance characteristics established during pilot-scale and field testing. The bench-scale characterization included ASTM analyses, specialty tests (such as the weak acid leaching of alkalies) and advanced analytical techniques (such as computer controlled scanning electron microscopy).

ABB CE's Fireside Performance Test Facility (FPTF) and B&W's Small Boiler Simulator (SBS) were used to evaluate the effects of coal properties on pulverization, ash deposition, combustion, erosion, and emissions.

Data and information from these tests were used to support CQE algorithm development, primarily in the areas of slagging and fouling, fly ash erosion, and boiler performance.

Utility Boiler Field Tests

CQE boiler field testing was vital in establishing correlations between field-, pilot- and bench-scale testing--correlations that were used to develop CQE algorithms and models.

Electric Power Technologies (EPT) and its subcontractors--the Fossil Energy Research Corporation (FERCO), Energy and Environmental Research Corporation (EER), and Southern Research Corporation (SoRI)--were responsible for utility boiler field testing. The team collected as-fired coal samples, measured boiler, pulverizer, and electrostatic precipitator performance, and assessed the real-time impacts of coal quality on power plant operations.

Comprehensive test burn evaluations were conducted at six utility test sites as summarized in Table S-6. Testing at each site consisted of a baseline coal test, in which the current unit coal supply was evaluated, and an alternate coal test, in which a coal or blend of improved quality was evaluated.

Table S-6
Utility Boiler Field Test Sites

PSO's Northeastern Unit 4	CE 445 MW tangentially fired supercritical unit
Mississippi Power Company's Plant Watson Unit 4	Riley Stoker 250 MW opposed-fired
Northern States Power King Unit 1	B&W 580 MW, cyclone-fired, supercritical boiler
Alabama Power Company Gaston Unit 5	CE 880 MW, twin furnace, tangentially fired boiler
New England Power Brayton Point Unit 3	B&W 620 MW horizontally opposed-fired boiler
New England Power Brayton Point Unit 2	CE 250 MW twin furnace, tangentially fired boiler

Each field test plan incorporated a unit boiler design data summary similar to that shown for Northeastern Unit 4 in Table S-7. The field test included the following major boiler designs:

- Tangentially fired drum boiler (CE)
- Tangentially fired supercritical boilers (two) (CE)
- Opposed-fired drum boiler (Riley Stoker)
- Opposed-fired supercritical boiler (B&W)
- Cyclone-fired boiler (B&W)

Test matrices similar to that shown for Northeastern Unit 4 (Table S-8) were developed for each field test unit.

Table S-7
Northeastern Unit 4 Boiler Design and Performance Data

Fuel Type	Coal
Boiler Type	CE - Tangential
Design pressure	4,000 (lb/sq.in.)
Steam flow	3,200 (m lb/hr)
Steam conditions:	
Superheat out	1,005°F (541°C), 3,597 psi
Reheat out	1,005°F (541°C), 618 psi
Turbine throttle pressure	3,500 psig
Design Excess air	25 percent
Fuel flow	529 klb/hr
Air Flow	--
Air heater temperatures:	
Flue gas in	795°F (424°C)
Flue gas out	260°F (127°C)
Air in	100°F (38°C)
Air out	720°F (382°C)
Boiler efficiency	86.36 percent
Surface area:	
Boiler/water walls	38,941 sq. ft.
Primary superheat	--
Secondary superheat	--
Reheat	--
Economizer	--
Furnace volume	365,616 cu. ft.
Furnace width	52 ft.
Design coal properties:	
Proximate (as-received) (Wt %)	
Moisture	30.0 percent
Volatile matter	32.6 percent
Fixed carbon	31.6 percent
Ash	5.8 percent
Grindability, HGI	55
Ash fusion temperature	2,210°F (1210°C)
Ultimate (as-received) (Wt %)	
Ash	5.8
Sulfur	NA
Hydrogen	NA
Carbon	NA
H_2O	30.0
N_2	
O_2	
Higher heating value	8,125 Btu/lb

Table S-8
PSO Northeastern Unit 4 Test Matrix

Test	Load (MWg)	O_2	Test Objective	Measurements
Baseline Coal (100 WY)				
A	480	Normal	Initial Full Load Characterization	B,C
B	480	Normal	Characterization of Boiler Variables	B,C
C	480	Normal	Burner Tilt Characterization	B
D	480	Normal	Full Load Operation	B,C,M
E	480	Low	Full Load Operation with Low O_2	B,C*
J	480	Normal	Detailed Full Load Characterization	B,C,M*,F,E
K	500	Normal	Maximum Load Test	B,C*,M*,F*
L*	480	Normal	Special Slagging/Fouling Tests	B*,C*,F*
Alternate Coal 1 (90 WY/10 OK)				
M	480	Normal	Initial Full Load Characterization	B,C
N	480	Normal	Characterization of Boiler Variables	B,C
O	480	Normal	Burner Tilt Characterization	B
P	480	Normal	Full Load Operation	B,C,M
Q	480	Low	Full Load Operation with Low O_2	B,C*
V	480	Normal	Detailed Full Load Characterization	B,C,M*,F,E
W	500	Normal	Maximum Load Test	B,C*,M*,F*
X	480	Normal	Boiler Perf/Slagging Optimization	B,C*,F*
Alternate Coal 2 (70 WY/30 OK)				
Y	480	Normal	Initial Full Load Characterization	B,C*
Z	480	Normal	Full Load Operation	B,C,M*,F*
AA	480	Low	Full Load Operation with Low O_2	B,C*
BB	480	Normal	Boiler Perf/Slagging Optimization	B*,C*,F*
CC	500	Normal	Maximum Load Test	B,C*,M*,F*

Notes:

* - Optional

B - Boiler monitoring (control room, gaseous, opacity, etc.)

C - Combustion performance (Loss of Ignition measurement or gas traverse)

M - Mill monitoring (fineness, vibration, rejects, etc.)

F - Furnace measurements (exit gas temperature or slagging/fouling)

E - ESP measurements (Volts/Amps, loading, size distribution, SO_3)

Coal Quality Impact Model (CQIM) models were developed for each unit tested. Because CQE incorporates CQIM, submodel predictions--such as boiler heat transfer, pulverizer, and precipitator models--were compared against field test data to validate the accuracy of CQIM. The objectives of the CQIM validation efforts were:

- To evaluate the accuracy of CQIM predictions versus test data.
- To assess the benefits of calibrating CQIM using detailed test burn data.
- To identify elements of the CQIM predictions in which test burn results or improved equipment models could be used to enhance the predictive capabilities of CQIM and CQE.

The field tests proceeded according to plan and the results satisfied the task objectives:

- Acquired technical data to distinguish between coal, operational, and equipment related effects.
- Identified strengths and weaknesses of CQIM.
- Investigated the use of new measurement techniques (e.g., deposition probes, non-intrusive hot gas measurement, infrared video imaging, on-line carbon in ash) to diagnose and quantify combustion phenomena.
- Established a technical basis for comparing field test results with pilot-scale combustion tests.
- Identified revisions to the Fireside Testing Guidelines that were incorporated into the Fireside Advisor.

Environmental Performance

One of the first steps in this project was the preparation of an Environmental Information Volume (EIV) to facilitate the U.S. Department of Energy's compliance with the National Environmental Policy Act (NEPA) of 1969. Discussions of the environmental, health, safety, and socioeconomic impacts associated with each utility field test were included in the EIV.

In addition, an approved Environmental Monitoring Plan (EMP) was prepared to:

- Document the extent of compliance monitoring activities (i.e., those monitoring activities conducted to meet permit requirements);
- Confirm the specific environmental impacts predicted in the EIV; and

- Establish an information base for the assessment of the environmental performance of the technology demonstrated by the project.

The EMP covered these issues for all six utility field test sites. Both compliance and supplemental monitoring were conducted to satisfy the requirements of the EMP. Compliance monitoring is that required by environmental agencies to demonstrate compliance with applicable regulations and permits, while supplemental monitoring included specific test measurements beyond compliance monitoring that were required to develop data for the Coal Quality Expert and associated documentation.

Environmental Monitoring Reports (EMR) were prepared throughout the course of the project and a final EMR was prepared for each field test site. Aside from a few excursions for opacity during the field tests that were caused by load changes or equipment problems, there were no violations of air quality or water discharge permits.

CQE

The comprehensive software tool, CQE, brings a new sophistication to fuel decisions by seamlessly integrating the system-wide effects of fuel purchase decisions on power plant performance, emissions, and power generation costs. CQE delivers this value by providing powerful technical capabilities, uncomplicated user interaction, increased flexibility, and information sharing.

CQE takes advantage of existing capability by integrating proven Electric Power Research Institute (EPRI) computer programs such as the Coal Quality Impact Model (CQIM™), the Coal Quality Information System (CQIS), and correlations from NOxPERT. It offers significant advances in assessing utility slagging and fouling issues by uniting other models developed under the CQE framework: SLAGGO and FOULER. The CCSEM approach offered by these tools allows greater confidence in modeling deposition phenomena through predictive capability in deposit growth, strength, and removability.

A user-friendly interface enhanced by extensive use of graphical tools collects and presents data within a powerful application framework and allows CQE to fulfill specific needs with different processes.

An Application guides users through an analysis by identifying the order in which activities should be performed and the information needed to successfully complete the analysis. Users can visually determine location within the analysis at all times by viewing a roadmap of the Application (Figure S-3). The roadmap provides the user with the decision framework of the Application currently executed.

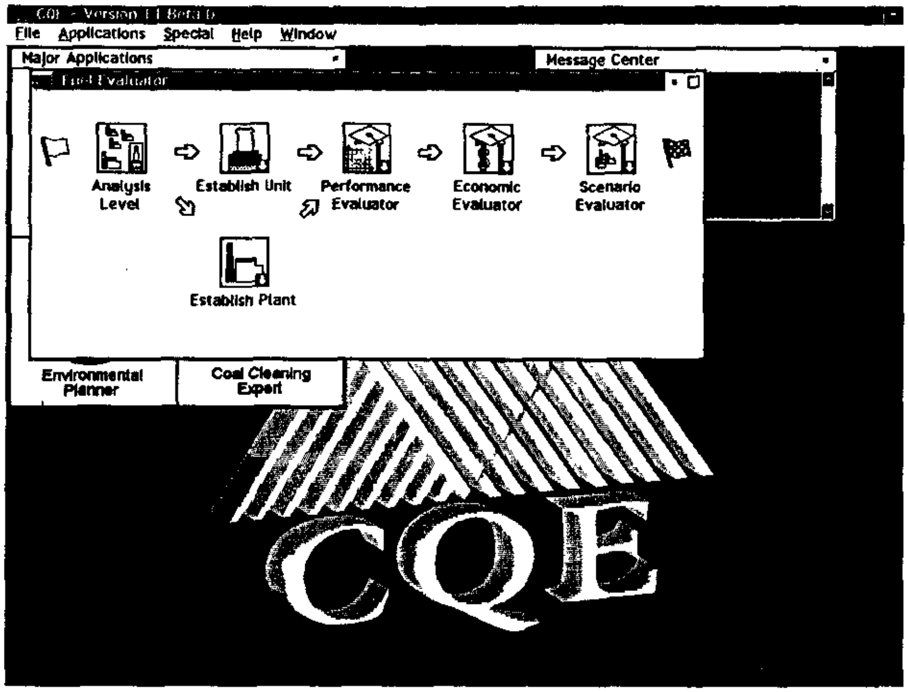


Figure S-3
CQE Application Roadmap

The Model Constructor assists in building and editing plant, unit and equipment system models. It facilitates data entry and model setup, assists the user by identifying essential data and provides the ability to store and retrieve data. In addition, the Model Constructor provides the ability to import CQIM model files and the ability to copy unit configurations (Figure S-4).

CQE output is presented in an Interactive Output Utility. The IOU presents calculational results in tables and graphs selected by the user (Figure S-5). Equipment system level performance results and data inputs are presented in notebooks. The IOUs also provide hardcopy output and data export to spreadsheets via Dynamic Data Exchange links.

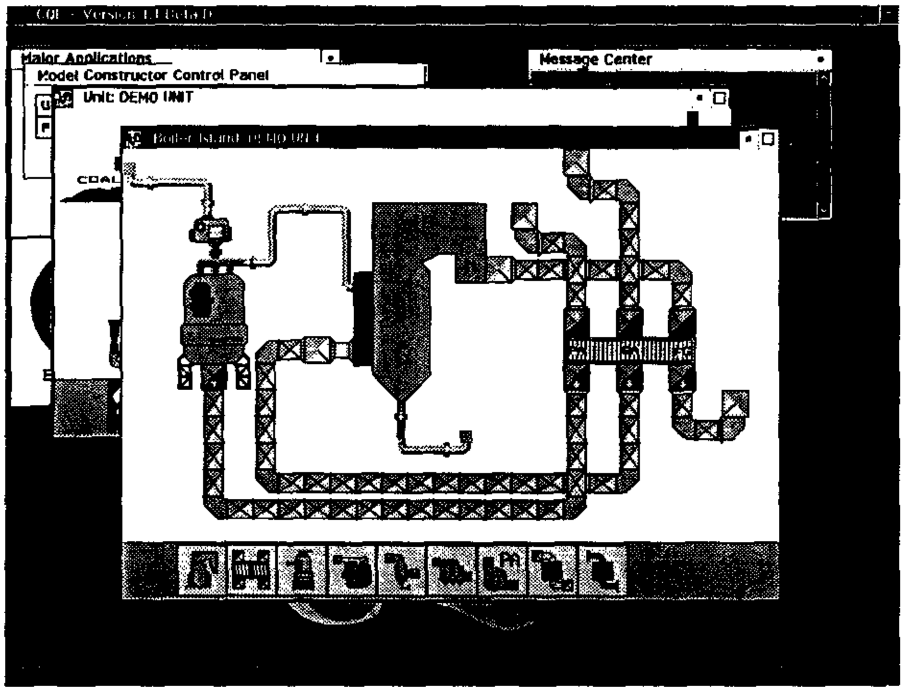


Figure S-4
CQE Model Constructor Streams

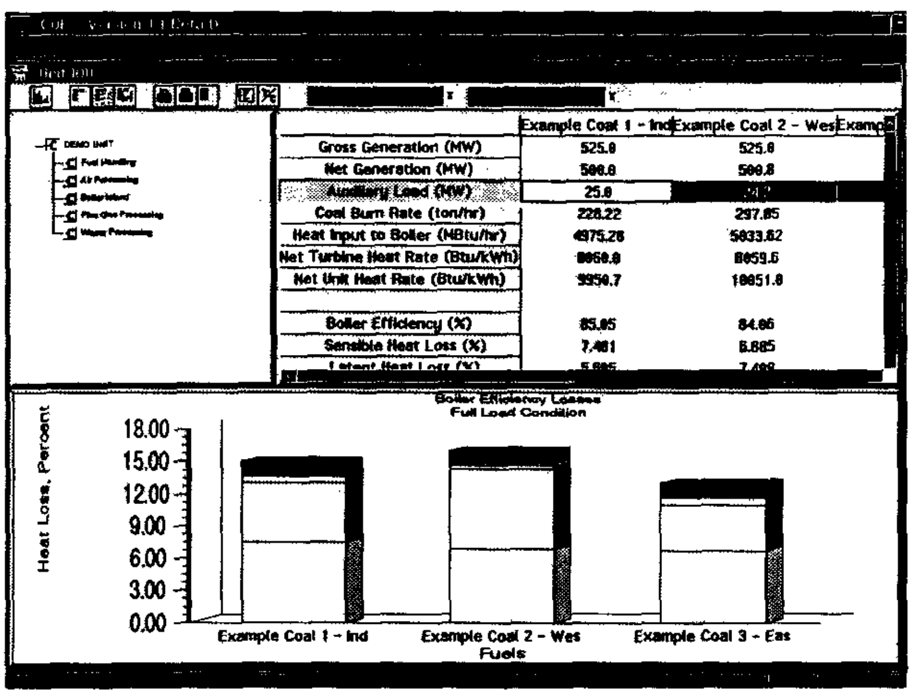


Figure S-5
CQE Interactive Output Utility

Commercialization Potential and Plans

An analysis of the market for CQE shows that the most likely customers for CQE are power generation organizations, fuel suppliers, environmental organizations, government organizations, and engineering firms. These world-wide organizations can take advantage of CQE's ability to evaluate the impact of fuel quality on entire generating systems.

CQE will be sold in the form of three types of licenses: use, consultant, and commercialization. The largest market for use licenses is to power generation organizations. The introductory price for a CQE use license is $100,000. Large architect/engineering firms and boiler manufacturers are most likely to purchase consultant licenses or regional or world-wide commercialization licenses.

CQ Inc. plans to service North America directly by marketing use and consultant licenses in the United States and Canada. CQ Inc. plans to market CQE using the following vehicles:

- Technical papers
- Magazine articles
- Magazine advertisements
- Direct contact (telephone)
- Internet (www.fuels.bv.com)
- Trade show demonstrations.

CQE will be distributed through EPRI to its membership, which includes approximately seventy percent of the public utilities in the United States. EPRI members receive CQE pre-paid as part of their EPRI dues. The marketing effort will be focused on utilities that are not EPRI members and the larger coal companies.

Conclusions and Recommendations

CQE will benefit coal-fired power plants in their commitments to produce energy economically and with concern for the environment. Utilities now have a tool to evaluate the system-wide consequences of fuel purchase decisions on power plant performance, emissions, and power generation costs. The software can examine potential changes in coal quality, transportation options, pulverizer performance, boiler slagging and fouling, emissions control alternatives and byproduct disposal for pulverized-coal and cyclone-fired power plants.

CQE will warrant further refinement and updating as new predictive models are refined and validated. Future development of CQE should include coal gasification, fluidized bed boilers, European and Asian boiler design, and post-combustion SO_2 and NO_x control technologies, including those successfully demonstrated in U.S. Clean Coal Technology projects.

1.0

INTRODUCTION

Increasing public awareness about the health of the global environment, tightening emissions regulations, growing competition among power producers, and advances in power generation technology are transforming the business of power generation worldwide. This transformation has further complicated fuel purchase decisions that profoundly affect the cost of electricity.

CQE™ (the Coal Quality Expert) is a software tool that brings a new level of sophistication to fuel decisions by seamlessly integrating the system-wide effects of fuel purchase decisions on power plant performance, emissions, and power generation costs.

The result of a $21.7 million U.S. Clean Coal Technology project sponsored by the Department of Energy and the Electric Power Research Institute, CQE offers unparalleled advancements in technical capability, flexibility, and integration.

1.1 Purpose of the Project Performance and Economics Report

This report will serve a two-fold purpose for the project sponsors, participants and prospective technology users:

- To inform readers of project results
- To provide an overview of the technology and its value for prospective users

Because the scope of the project included coal characterization, bench- and pilot-scale combustion testing, and full-scale utility demonstration tests in addition to software development and demonstration tasks, and because these efforts involved the collection of thousands of pages of technical data, it is impractical for this Project Performance and Economics Report to include all data that may be of interest to DOE and its constituents. These data are available in raw form, in summaries that have been published as technical papers, project quarterly reports, and published EPRI reports and they are summarized even further in later sections of this report. These data represent the results from the largest single effort ever to document the impacts of coal quality and power plant operation practices on emissions and power production costs.

The CQE technology, which addresses fuel quality from the coal mine to the busbar and the stack, is an integration and improvement of predecessor software tools including:

- EPRI's Coal Quality Information System
- EPRI's Coal Cleaning Cost Model
- EPRI's Coal Quality Impact Model
- EPRI's NO_x Formation Model
- EPRI and DOE models to predict slagging and fouling
- EPRI's Electrostatic Precipitator Model

CQE can be used as a stand-alone workstation or as a network application for utilities, coal producers, and equipment manufacturers to perform detailed analyses of the impacts of coal quality, capital improvements, operational changes, and/or environmental compliance alternatives on power plant emissions, performance and production costs. It can be used as a comprehensive, precise and organized methodology for systematically evaluating all such impacts or it may be used in pieces with some default data to perform more strategic or comparative studies. This report underscores the credibility of the developments and demonstration of the CQE technology and it supplements previous project publications and the user's manual.

1.2 Overview of the Project

The CQE project was conceived by EPRI to integrate the results and products of several on-going R&D projects into computer software that would become a worldwide standard for addressing fuel-related issues in the power industry. EPRI and DOE sponsored numerous coal quality R&D projects in the late 1970s and early 1980s to carefully examine and document the answers to questions that need to be addressed before a utility can be certain that it is operating its power plants within emissions limitations at the lowest possible cost:

- How would the delivered price of coal change if the supplier cleans or blends the coal(s) to produce a product with quality characteristics different than the coal currently delivered to the power station?

- To what degree can the quality of the coal currently delivered to the power station be changed?

- What power plant equipment and systems are most affected or limited by coal quality?

- What are the trade-offs between increased capital spending at the power stations and increased cost of fuel for higher quality?

- How will alternative emissions control strategies affect the production cost of electricity at a specific unit?

- Are the slagging and fouling consequences of burning a prospective coal affordable?

- Based on laboratory and bench-scale testing, what are the economics of burning a prospective coal?

Coal producers and equipment manufacturers must also address these questions from a different perspective to assess the potential value of alternative products and services for utilities. For example, a coal producer contemplating changes to an existing cleaning plant or a manufacturer trying to sell replacement parts for coal pulverizers would both be interested in using a model that could accurately determine pulverizer performance, power consumption, and maintenance costs for potential utility customers. CQE was conceived as the tool to serve the needs of these prospective users.

1.2.1 Background and History of the Project

In the mid 1970s, EPRI initiated its effort to understand the linkage between coal quality and power plant performance, emissions, and economics. Initial studies focused on the potential savings in capital cost of new coal-fired power stations that would result from the use of cleaner coal (1). To quantify the costs of producing cleaner coals and to evaluate the potential for physical coal cleaning to improve the quality of U.S. coals for power generation, EPRI initiated a coal cleanability characterization program at the Coal Cleaning Test Facility (CCTF), which it constructed in 1980-81. The facility's mission also included the demonstration of emerging coal cleaning technologies to accelerate their commercial deployment.

In 1982, EPRI started a parallel effort to build a state-of-the-art computer model that would predict power plant performance, production costs, and emissions based on laboratory and bench-scale coal quality measurements. The initial effort was focused on defining the specifications for the model and assembling the proven methodologies for predicting coal quality impacts on various power plant systems and components. A complementary effort to perform laboratory, bench-scale, and pilot-scale coal quality analyses was also initiated by EPRI in the mid 1980s, and because the Coal Cleaning Test Facility became the source for most of the combustion test samples, its name was changed to the Coal Quality Development Center (CQDC).

When the DOE Program Opportunity Notice for the Clean Coal Technology Program was issued on February 17, 1986, Combustion Engineering Inc. on behalf of EPRI prepared a proposal for the development of the Coal Quality Advisor that was later renamed the Coal Quality Expert or CQE. The project proposed by Combustion Engineering included coal cleanability characterization of selected additional U.S. coals, laboratory, bench-scale, and pilot-scale combustion testing of representative samples of the run-of-mine and clean coal; full-scale power plant testing of those coals to verify coal quality effects; and the development of the software tool that would replace pilot-scale and full-scale demonstrations in the future. The proposal by Combustion Engineering was not selected from the initial awards for Round 1 of the Clean Coal Technology Program, so EPRI proceeded with some aspects of the proposed project in the meantime.

By the time the Combustion Engineering proposal was selected for negotiations in 1988, EPRI had completed an initial version of the Coal Quality Impact Model and initiated some pilot-scale and commercial power plant testing programs. The result of these efforts and the previous work done by EPRI at the CQDC (and CCTF) were contributed by EPRI to the CQE project and the scope of the project was redefined to incorporate the testing and software development work necessary to complete a competent model.

During the course of the project from May 1990 through mid-1996, computer technology and the methodology available to measure and predict coal quality continued to advance, so CQE was developed to incorporate as many of these advancements as possible and to maintain the flexibility to incorporate new features or update existing methodologies economically in the future.

Table 1-1 is a chronology of the project.

1.2.2 Project Organization

As EPRI's contractor with responsibility for bench-scale and pilot-scale testing to correlate coal quality characteristics to power plant performance, Combustion Engineering (now ABB CE) submitted the proposal for the CQE project to DOE. While the DOE CCT1 project award decisions were being made, EPRI engaged Black & Veatch to develop the original Coal Quality Impact Model software and Electric Power Technologies to conduct full-scale power plant coal quality impact tests. In addition, coal cleanability characterization efforts continued at the CQDC and EPRI developed plans to establish the CQDC as EPRI's wholly-owned subsidiary.

When DOE selected the CQE project for negotiation, EPRI and Combustion Engineering felt that it was appropriate for CQ Inc., EPRI's subsidiary, to integrate and manage the efforts of the project team as shown on the project organization chart, Figure 1-1.

Under this organization, both CQ Inc. and Combustion Engineering executed the Cooperative Agreement with DOE and both contractors became co-prime contractors for the project with project management and administrative duties being delegated to CQ Inc. Consequently, the project was organized so that each participating organization other than EPRI and DOE would be subcontractors to CQ Inc.

As new computer technologies developed during the project and as the definition of CQE became more defined, some logical changes were made in the project organization. GUILD Inc. (formerly ExpertEase) provided consultation, but the software coding responsibilities were centralized at Black & Veatch. When a decision was made to exclude the Fireside Troubleshooting Guideline from the CQE code, Karta Technologies' role on the project ended, and when CQ Inc. needed some assistance with the design of the coal cleaning and blending models, Decision Focus was added to the project team as another subcontractor. The roles of the University of North Dakota Energy and Environmental Research Center (UNDEERC) and

Table 1-1
Chronology of the Project

Date	Event/Activity
February 17, 1986	PON Issued
July 18, 1990	Project Kickoff Meeting - CQ Inc.
August 1, 1990	Northeastern Station Coal Characterization Completed
November 24, 1990	Watson Station Field Tests Completed
December 4-6, 1990	Power Gen '90 Exhibit - Orlando
December 14, 1990	Northeastern Station Field Tests Completed
January 15-16, 1991	Project Review Meeting - ABB/CE
March 18, 1991	Watson Station Coal Characterization Completed
April 3-5, 1991	World Coal Institute Exhibit - London
April 12, 1991	Northeastern Station Pilot Combustion Tests Completed
April 30 - May 2, 1991	Coal Prep '91 Exhibit - Lexington
June 5-6, 1991	Project Review Meeting - UNDEERC
July 19, 1991	Watson Station Pilot Combustion Tests Completed
July 30, 1991	Acid Rain Advisor Completed
November 13-14, 1991	Project Review Meeting - King Station
November 22, 1991	King Station Field Tests Completed
December 4-6, 1991	Power Gen '91 Exhibit - Tampa
January 23, 1992	King Station Pilot Combustion Tests Completed
February 1, 1992	Software Specifications Completed
May 5-7, 1992	Coal Prep '92 Exhibit - Cincinnati
May 20-22, 1992	Project Review Meeting - EPRI
June 30, 1992	King Station Coal Characterization Completed
June 30, 1992	Gaston Station Coal Characterization Completed
June 30, 1992	Gaston Station Pilot Combustion Tests Completed
October 29, 1992	Gaston Station Field Tests Completed
November 16-20, 1992	Power Gen '92 Exhibit - Orlando
March 27, 1993	NEP Brayton Point 3 Field Tests Completed
April 14-15, 1993	Project Review Meeting - Brayton Point Station
April 29, 1993	NEP Brayton Point 2 Field Tests Completed
September 8-9, 1993	2nd Annual DOE CCT Conference Exhibit - Atlanta
March 1995	CQE Alpha Version Completed
June 1995	CQE Beta Version Completed

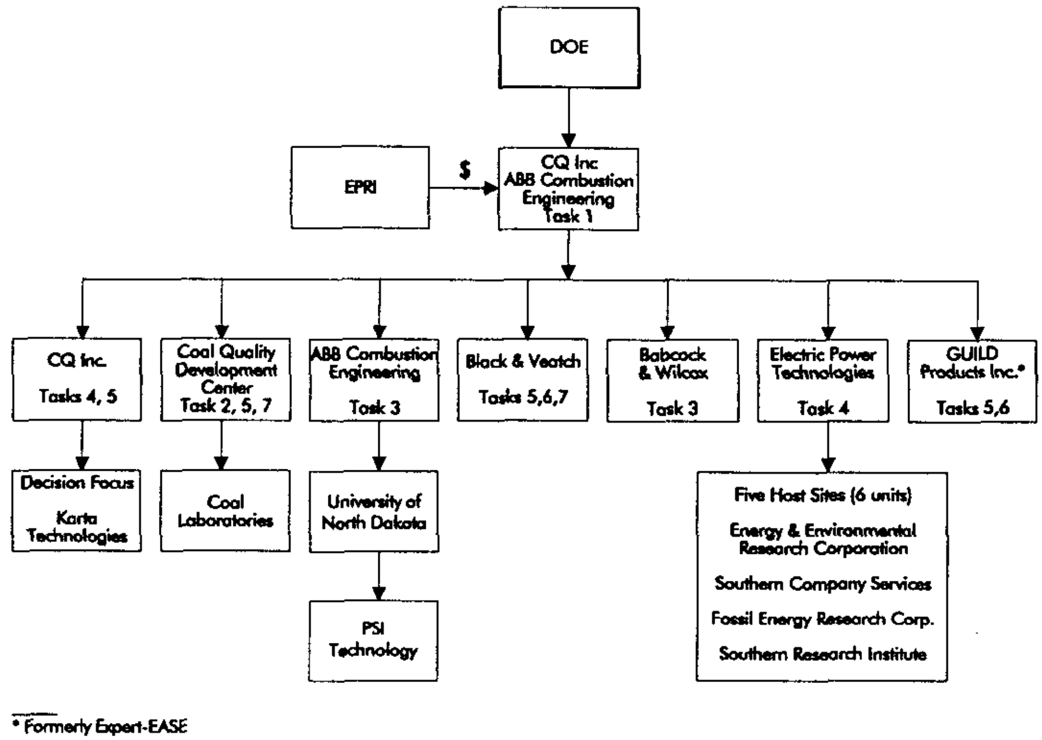


Figure 1-1
Project Organization Chart

PSI Technology were also expanded to include the delivery of fouling and slagging prediction methodology to Black & Veatch.

In recognition of the value of CQE to their customers and to continue their support of EPRI's and DOE's coal quality R&D programs, ABB CE willingly reduced its scope and budget on the project to provide funding for more robust slagging and fouling models for CQE. ABB CE led the efforts with UNDEERC and PSI Technology, which distinguish CQE from other software tools that rely on empirical indices to indicate potential slagging and fouling problems.

In addition to its role as co-sponsor, EPRI also provided technical leadership to the project for the pilot-scale and full-scale power plant testing programs and directly managed the software development tasks. EPRI's CQIM User's Group provided a sounding board for CQE development ideas and served as a project advisory committee. Moreover, five members of the user's group served as beta test users of the prototype software.

1.2.3 Project Description

Although the project mission was to deliver a software tool, the scope of the project included numerous supporting tasks to collect and analyze data to form the basis for CQE algorithms, methodologies and submodels and to verify the accuracy and integrity of the CQE software at the conclusion of the project. The project tasks are described in Table 1-2.

At the conclusion of each testing program, the responsible contractor prepared a detailed report and data summary for use by the host utility to address near-term problems and objectives and by the other CQE project contractors in completing their assigned tasks. The data were carefully stored by each responsible contractor so that any other contractor would have access to the details behind the data summaries, upon request.

Project review meetings were held at various contractor's facilities and at host utility power stations. These meetings, which were held as often as quarterly during peak project activity periods, supplemented project communication activities and provided a forum to plan and critique the CQE software design. In addition, the meetings served as technology transfer seminars for the project team participants, sponsors, and host utilities.

Table 1-2
CQE Work Scope

Test Sites	ABB/CE	B&W	B&V	CQ Inc.	UNDEERC	EPT	GUILD
Northeastern	5 DTFS 5 FPTF	NA	need FT/PT/BT data	2 CCC	4 DTFS 5 SEM	3 FT	NA
Watson	2 DTFS 2 FPTF	NA	need FT/PT/BT data	2 CCC	2 DTFS 2 SEM	2 FT	NA
King	NA	2 SBS	need FT/PT/BT data	5 CCC	2 SEM	2 FT	NA
Gaston	1 DTFS 1 FPTF	NA	need FT/PT/BT data	2 CCC	NA	2 FT	NA
Brayton Point	NA	NA	need FT data	NA	NA	2 FT	NA
Brayton Point	NA	NA	need FT data	NA	NA	2 FT	NA
Other CQE Work	commercial applications	NA	CQE software developer, CQIM enhancements, ARA	Coal Cleaning Cost Model, CQIS enhancements, select CQE test sites	ash deposition data & model inputs	Fireside Testing Guidelines	develop CQE shell specs

CCC--Coal Cleanability Characterization
SBS--Small Boiler Simulator (Pilot Test)
BT--Bench Test
DTFS--Drop Tube Furnace System
FT--Field Test
PT--Pilot Test
FPTF--Fireside Performance Test Facility (Pilot Test)
SEM--Scanning Electron Microscopy

The highlights of project accomplishments are shown in Table 1-3.

Table 1-3
Project Accomplishments

Accomplishment	Date
DOE awarded Cooperative Agreement	5/3/90
First of six field tests started	7/90
Pilot and bench scale testing started	11/90
CQE specifications completed	2/15/92
Pilot and bench scale testing completed	6/92
Acid Rain Advisor--first commercial product--released and copy sold	3/93
Completion of all six field tests	4/93
CQ Inc. and B&V signed CQE commercialization agreements	10/13/93
Conceptual design of the general Interactive Output Utility completed	8/94
Partially functional CQE beta version successfully tested	12/94
CQE alpha-version completed	3/31/95
CQE beta version completed and released for testing	6/95
Beta testing complete	11/30/95
CQE revised and issued on CD ROM	12/95
CQE Release 1.1 beta issued	6/7/96

CQE builds on existing correlations from worldwide R&D on the impacts of coal quality for specific parts of the total power generation system. CQE features EPRI's Coal Quality Impact Model (CQIM™) as the calculational foundation for determining the impacts of different coals on plant performance and costs. Southern Research Institute's models address electrostatic precipitation. EPRI's Coal Quality Information System (CQIS™) provides a national database of coal quality information. Similarly, NO_x retrofits are developed from NOxPERT model results.

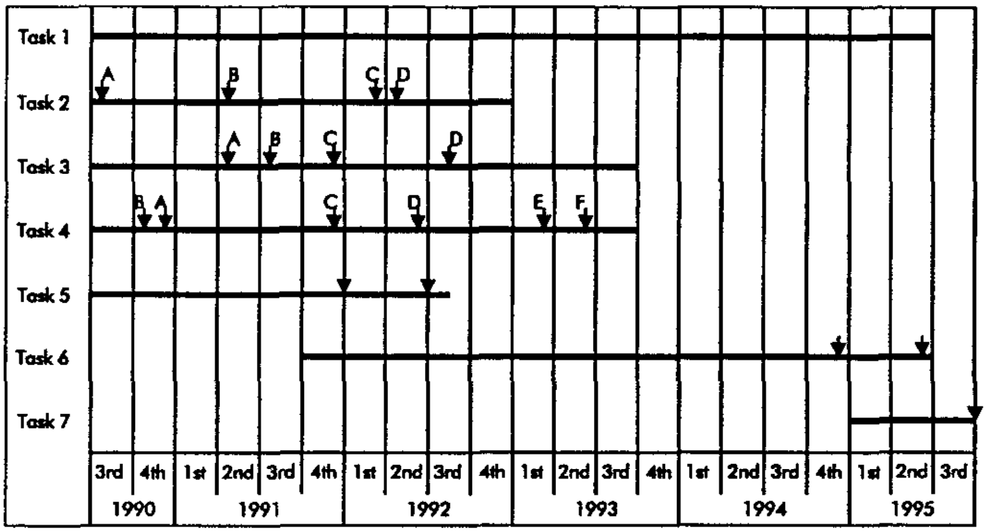
CQE combines the expertise from these established models--or the models themselves--into a single, personal computer-based tool. The electronic consultations that occur transparently between CQE's models let users address all aspects of fuel issues and their corresponding impacts on power generation systems.

This groundwork of established models is complemented by new and enhanced models derived from bench-, pilot-, and full scale test programs. These test programs, which allow coal-related effects to be distinguished from operational or design impacts, are among the most extensive of their kind ever conducted to relate power plant performance and emissions to coal quality.

1.2.4 Project Schedule

The original 42-month project actually spanned 64 months because the required "off-the-shelf" software for OS/2 was late and there were some delays in EPRI's funding resulting from their budget limitations in specific calendar years.

The longer-than-expected time span of the project required some increased funding from EPRI and DOE, but it ensured that CQE was adequately planned and that CQE's underlying computer software was adequately proven. The project schedule is given in Figure 1-2.



Task 1 - Project Management
Task 2 - Coal Cleanability Characterization
Task 3 - Pilot-Scale Combustion Testing
Task 4 - Utility Boiler Field Testing
Task 5 - CQIM Completion & Development of CQE Specifications
Task 6 - CQE Development
Task 7 - CQE Workstation Testing and Validation

Complete Test Runs or Major Milestone

Figure 1-2
Project Schedule

1.3 Objectives of the Project

The work falls under DOE's Clean Coal Technology Program category of "Advanced Coal Cleaning." The 64-month project provides the utility industry with a PC software program to confidently and inexpensively evaluate the potential for coal cleaning, blending, and switching options to reduce emissions while producing the lowest cost electricity. Specifically, this project:

- Enhanced the existing Coal Quality Information System (CQIS) database and Coal Quality Impact Model (CQIM) to allow confident assessment of the effects of cleaning on specific boiler cost and performance.

- Developed and validated a methodology, Coal Quality Expert (CQE), which allows accurate and detailed predictions of coal quality impacts on total power plant capital cost, operating cost, and performance based upon inputs from inexpensive bench-scale tests.

1.4 Significance of the Project

Originally, coal cleaning technologies were used only to remove ash-forming mineral matter. After passage of the 1970 Clean Air Act, coal cleaning processes were applied to a second purpose--sulfur reduction--accomplished primarily by removing the sulfur-bearing mineral pyrite. A great deal of geochemical information concerning the modes of occurrence of pyrite in coal was gathered and used to develop new methods of sulfur removal and to enhance existing methods. Today, coal cleaning plays a larger role in controlling SO_2 emissions than all post combustion control systems combined. It has led to reduced SO_2 emissions while U.S. coal use by utilities has increased steadily since 1970 (see Figures 1-3 and 1-4).

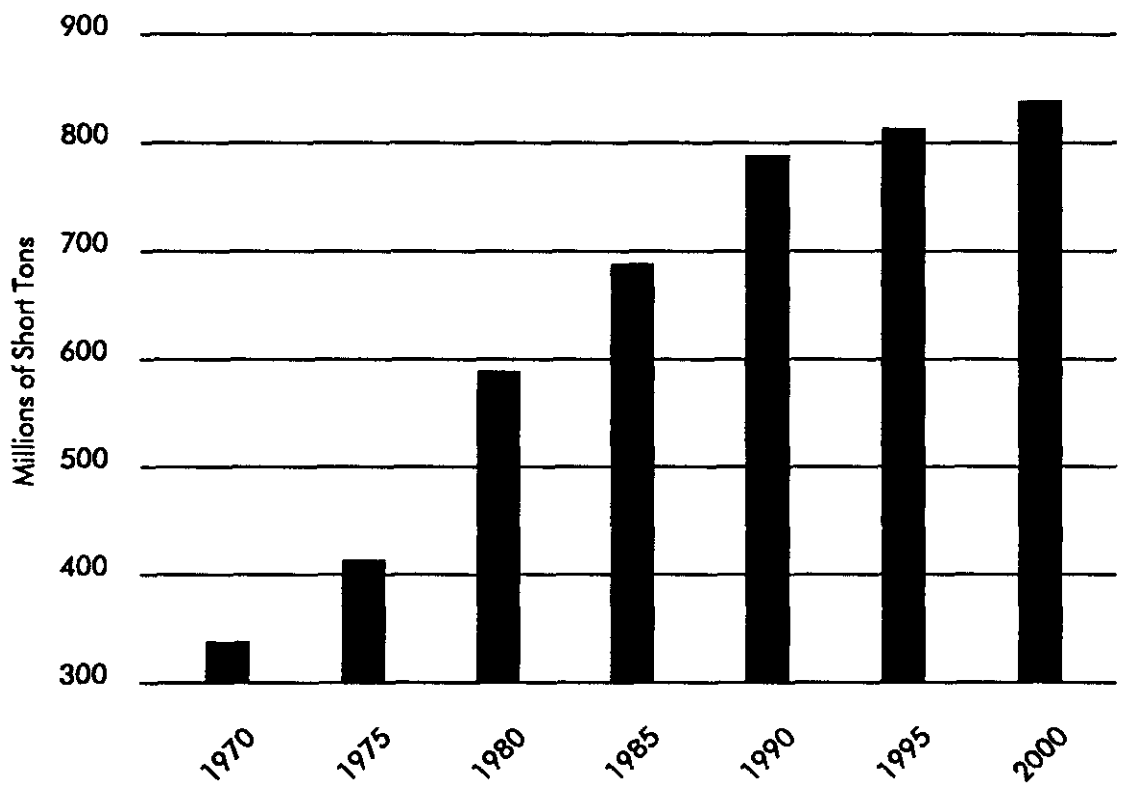


Figure 1-3
U.S. Utility Coal Use

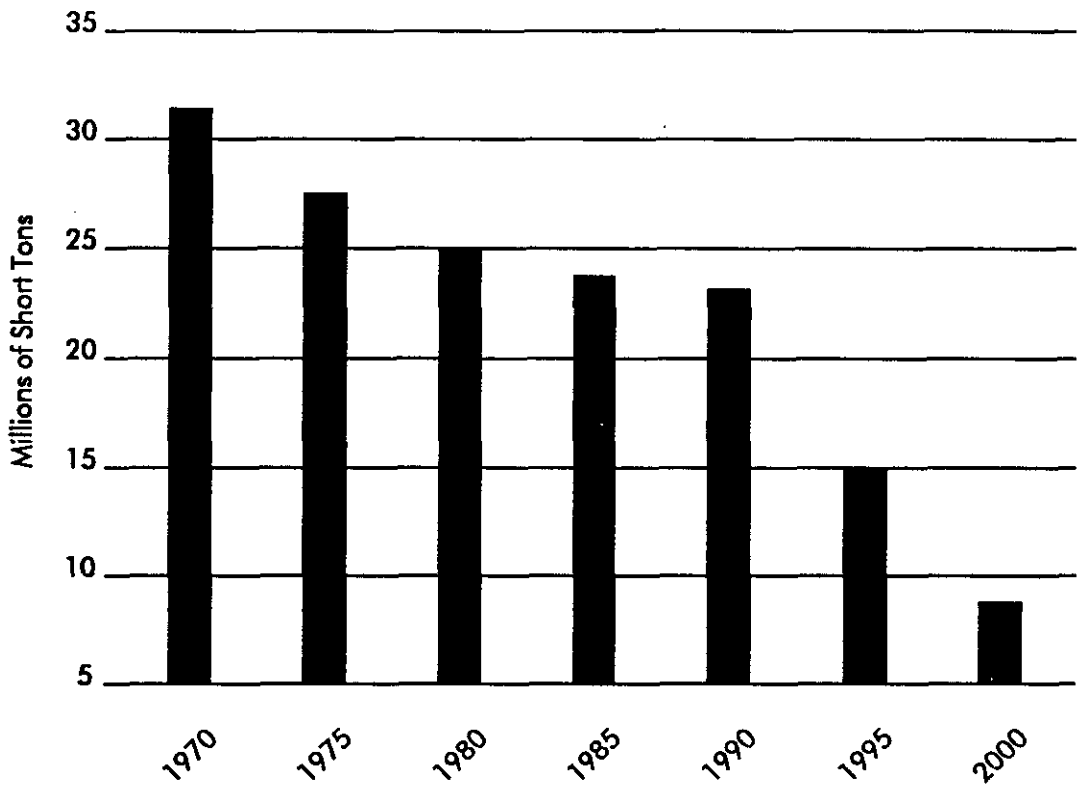


Figure 1-4
Total U.S. SO_2 Emissions

Coal cleaning has been commercially demonstrated as a means of reducing sulfur concentrations in some types of coal to levels which allow firing in boilers to conform to environmental standards without using scrubbers. In addition, coal cleaning reduces the concentrations of mineral impurities which may result in significant improvements in boiler performance, reduced maintenance, and increased availability. Figures 1-5 and 1-6 illustrate trade-offs which dictate the feasibility of coal cleaning. Sulfur emissions produced when burning a coal generally decrease with increased levels of cleaning. Fuel costs, however, increase with increased levels of cleaning (Figure 1-5). Another consideration is that fuel performance benefits increase with increased cleaning for existing units and improved fuel performance reduces new unit capital costs (Figure 1-6).

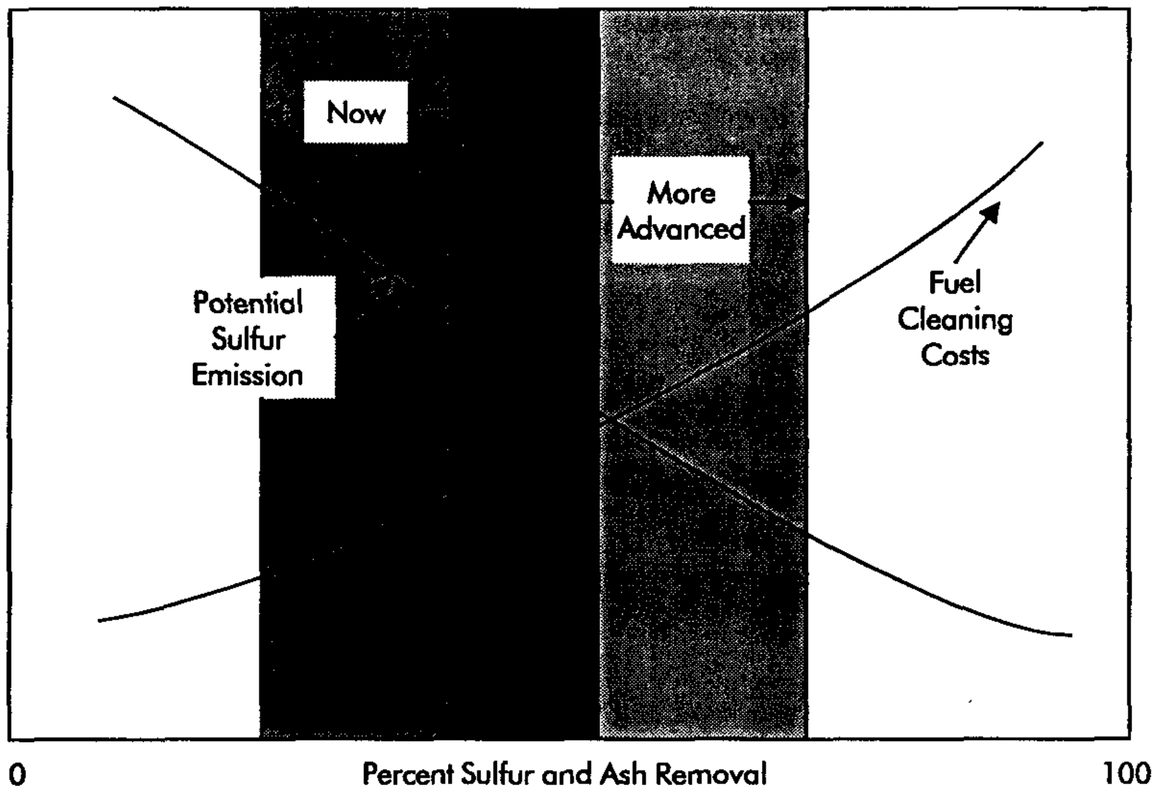


Figure 1-5
The Relationship Between Sulfur Emissions and Fuel Costs

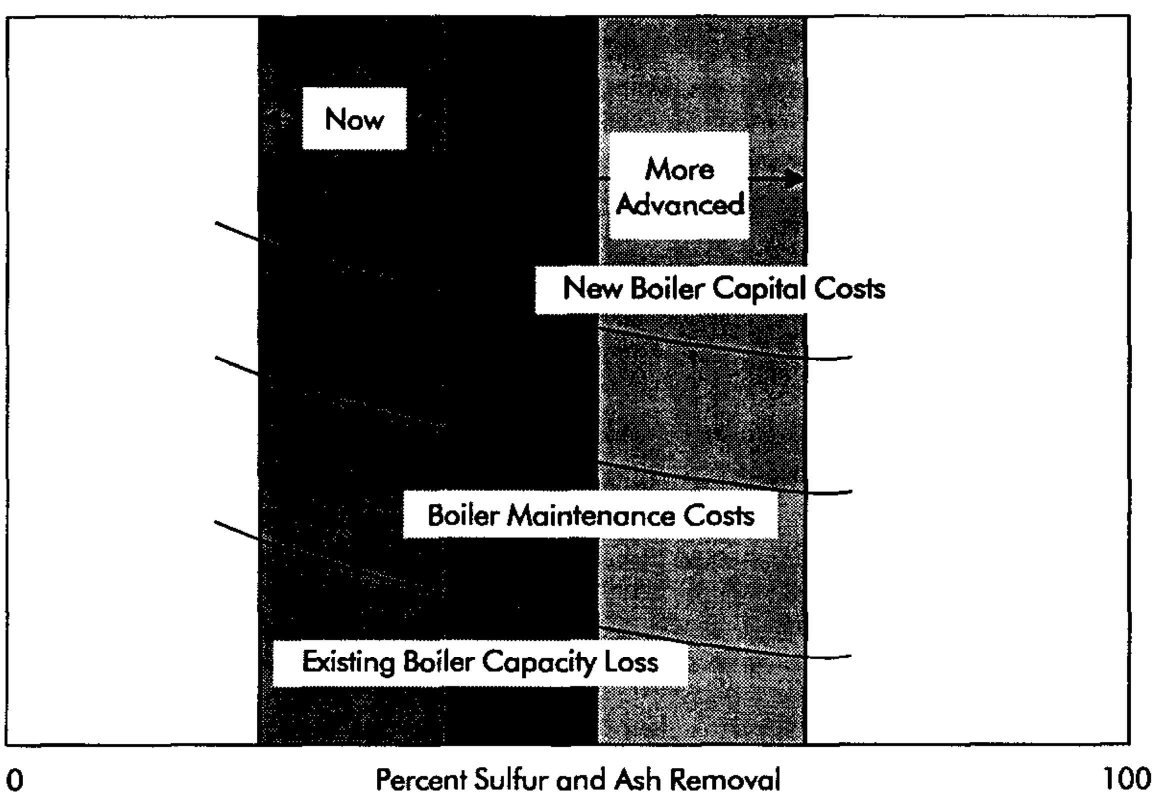


Figure 1-6
Coal Cleaning to Reduce Power Production Cost

Recent studies have indicated significant economic benefits resulting from coal cleaning (2). However, to accurately and completely assess the commercial viability of cleaning a particular coal, detailed large-scale combustion testing is necessary. Quantification of performance savings is necessary to compare the economic benefits obtainable through coal cleaning with the costs of other techniques for emission control. Industry currently does not have the capability to reliably predict the performance of cleaned coals without extensive studies. The relationship between level of confidence and testing coals is illustrated in Figure 1-7. Because many of today's bench-scale coal performance indices rely on empirical correlations (some without sound fundamental bases), extrapolation of these indices to fuels not represented by the specific database used for correlation can be misleading. The need for quick, inexpensive tests that can be reliably used to assess the commercial impacts of coal cleaning is vital to implement clean coal technology. One of the major goals of the proposed program is to develop and demonstrate simple techniques (bench-scale fuel properties and predictive models) that will allow industry to confidently assess the overall impacts of coal quality and the economic implications during utilization (Figure 1-8).

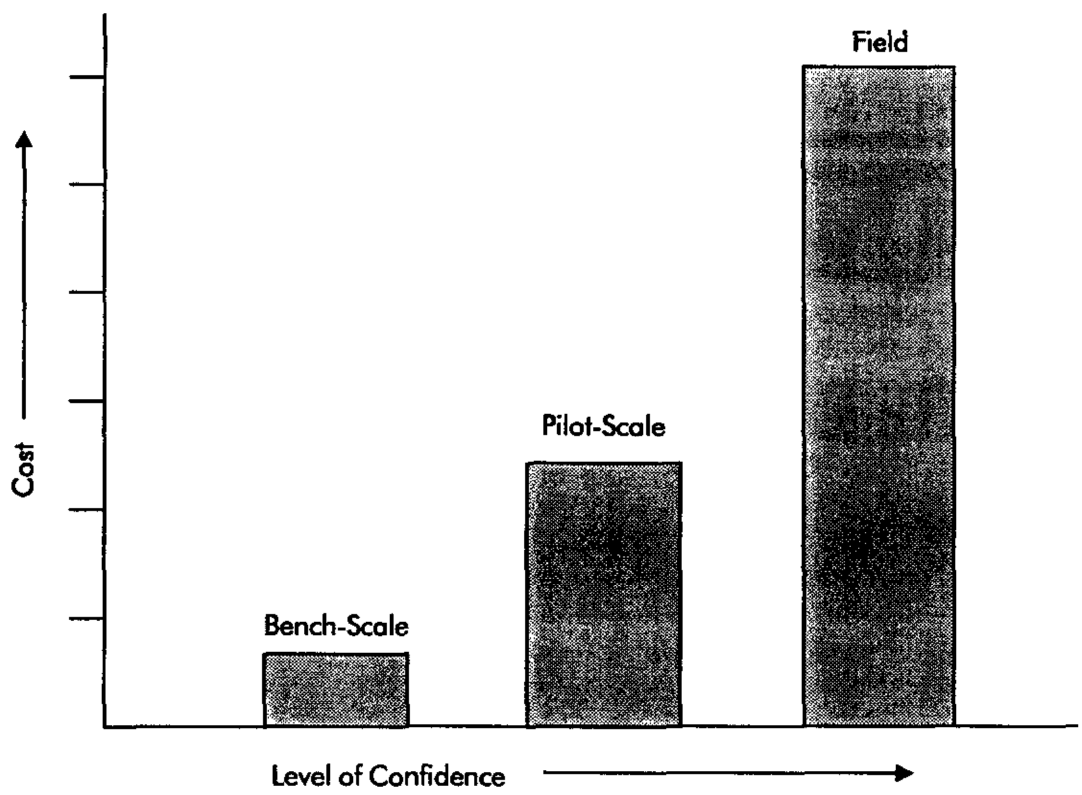


Figure 1-7
Relationship Between Testing Cost and Confidence Level of Commercial Predictions

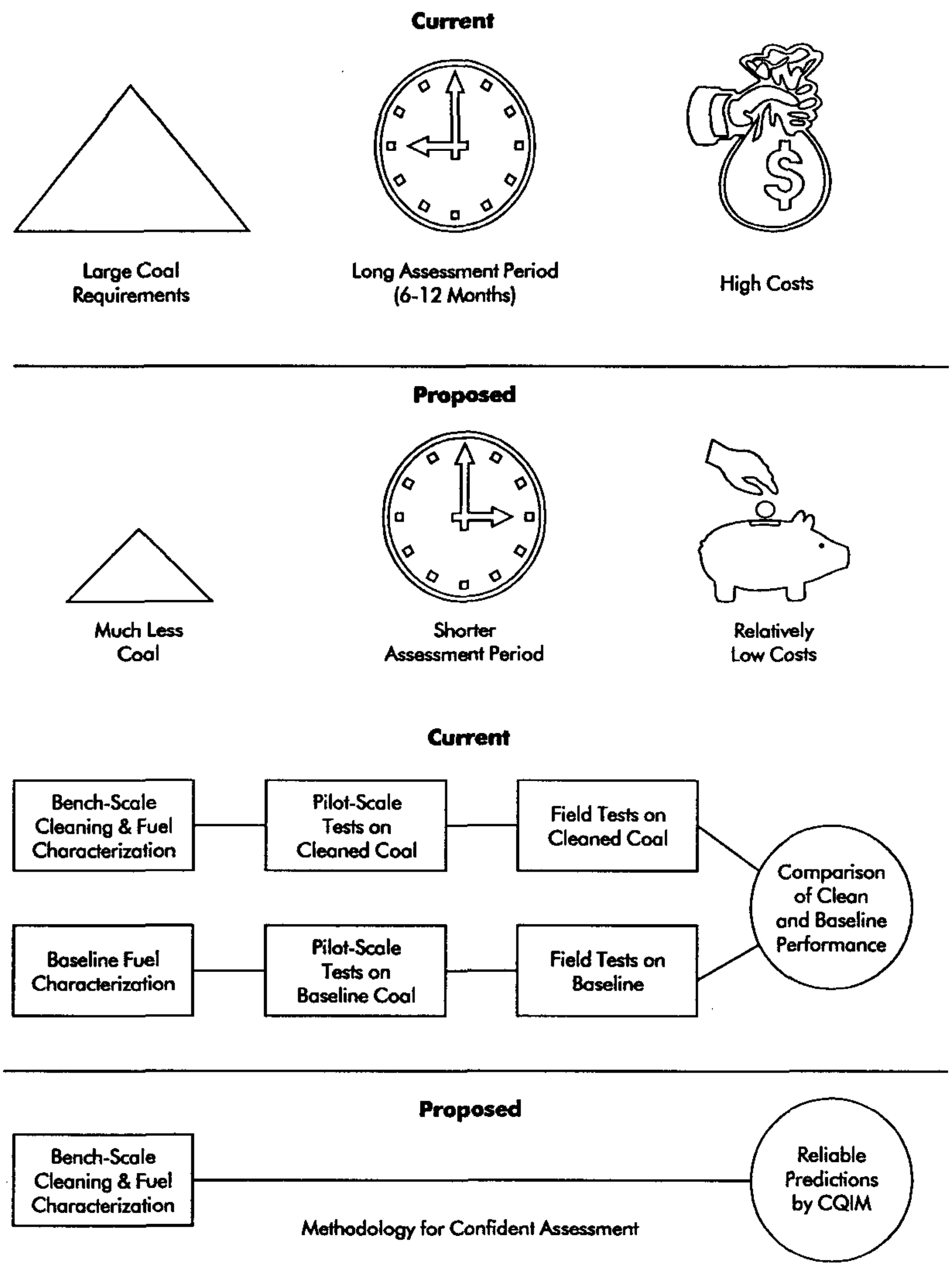


Figure 1-8
Comparison of Assessment Methods

Fuel decisions affect nearly every aspect of power generation. Fuel buyers handle transportation issues and coal sourcing; plant engineers evaluate how individual coals behave in a unit; and environmental engineers address compliance and disposal issues. Typically, each expert uses an individual set of assumptions, data, and tools to complete an evaluation, resulting in one-dimensional pictures of fuel-related costs.

CQE integrates these assumptions, data, and tools, creating a unique electronic forum within which experts can efficiently and effectively share their knowledge and results.

The power of the forum is twofold. It not only centralizes all relevant information, it makes that information available to all other experts as appropriate. The end result of integrating a set of previously isolated analyses is a new capability that provides a complete picture of fuel-related impacts and costs.

One new capability, for instance, is CQE's ability to evaluate the economic tradeoffs between coal cleaning and scrubbing (Figure 1-9). Traditionally, utility engineers would combine results from two different models to compare the costs of cleaning and scrubbing. In contrast, a CQE analysis of cleaning versus scrubbing captures and consolidates the results of required analyses to determine the most cost-effective option or combination of options.

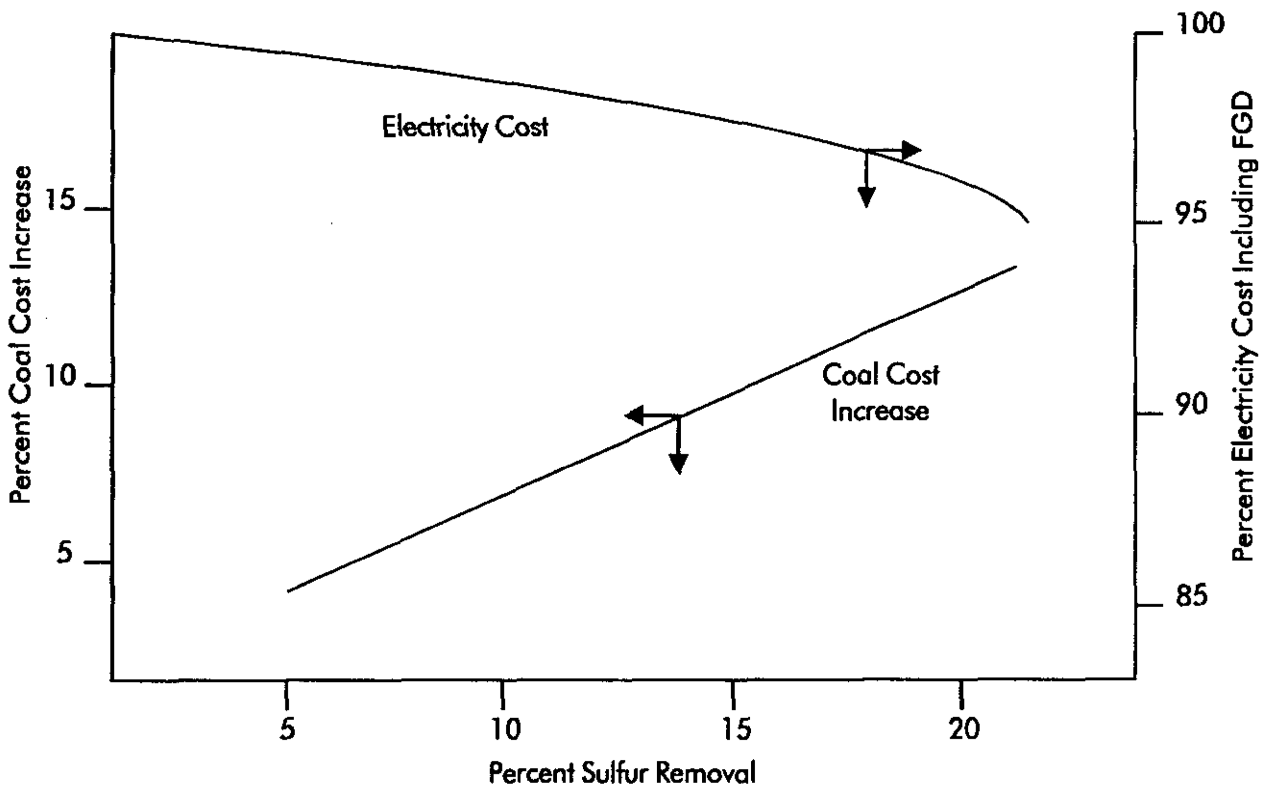


Figure 1-9
Economic Impact of Coal Cleaning

1.5 DOE's Role in the Project

The U.S. Department of Energy's Clean Coal Technology Program was established to accelerate the commercialization of new technologies for reducing acid rain precursors--SO_2 and NO_x. Technologies that also improve the efficiency of power generation provide the added benefits of increasing U.S. competitiveness and reducing emissions of other combustion by-products such as CO_2 and trace elements that have been identified as potential air toxics. The CQE technology was selected for award by DOE because coal cleaning not only serves to remove mineral matter from the coal that leads to lower emissions, but also produces a more energy-intensive fuel that can reduce power generation costs and increase power plant efficiency. Persuasive evidence of the benefits of coal cleaning proves that optimizing coal quality through cleaning, blending, or switching is crucial to effective power plant utilization, and DOE selected this project because it will deliver the software that will lead to such optimization.

During the project, DOE provided sustained funding and oversight to ensure that project goals were met on a schedule that would deliver the CQE technology in time for it to be used by utilities making compliance decisions for Phase II of the Clean Air Act. As a result of increasing competition in the utility industry, uncertainty about the future regulatory environment, and the low profitability of the coal and utility industries at present, it is unlikely that the CQE technology would have been completed on this schedule by EPRI and its constituents. DOE's funding and its requirements for 50 percent cofunding provided incentives to EPRI and its constituents, and ensured the continuity of their efforts.

DOE's oversight and reporting requirements also ensured that project activities were not easily abandoned or diverted to other interesting, but not important, issues. DOE, EPRI, and the project participants were flexible enough to re-define project scope and tasks when appropriate, but DOE's involvement made the participants, contractors, and sponsors more accountable for such decisions.

Finally, DOE has played, and hopefully will continue to play, an important role in the technology transfer and promotion of the CQE technology. DOE's project manager and other professionals have escorted delegations of foreign visitors to CQ Inc. headquarters for demonstrations of the CQE technology, DOE has publicized the project and its results, and DOE conferences have provided an appropriate forum for the software commercializers to promote the product.

1.6 References

1. *Coal Preparation for Combustion and Conversion*, EPRI AF-791, Project 466-1 Final Report, May 1978, Gibbs & Hill Inc., NV.

2. *Impact of Coal Cleaning on the Cost of New Coal-fired Power Generation*, EPRI CS-1622, Project 1180-2 Final Report, May 1981, Bechtel National Inc., San Francisco, CA.

2.0

TECHNOLOGY DESCRIPTION

The comprehensive software tool, CQE, brings a new sophistication to fuel decisions by seamlessly integrating the system-wide effects of fuel purchase decisions on power plant performance, emissions, and power generation costs. CQE delivers this value by providing powerful technical capabilities, uncomplicated user interaction, increased flexibility, and information sharing.

The PC-based program evaluates coal quality, transportation options, performance issues, and alternative emissions control strategies for utility power plant systems. CQE is composed of technical tools to evaluate performance issues; environmental models to evaluate emission and regulatory issues; and economic models to incorporate production costs such as consumables (fuel, scrubber additive, etc.), waste disposal, operating and maintenance, replacement energy costs, and costs for installation of new and retrofit coal cleaning processes, power production equipment, and emissions control systems. These technical, environmental, and economic models have been integrated into a user-friendly interface enhanced by extensive use of graphical tools to collect and present data within a powerful application framework that allows CQE to fulfill specific needs with different processes. Fully network-aware, CQE seamlessly shares data across networks and between users.

CQE takes advantage of existing capability by integrating proven Electric Power Research Institute (EPRI) computer programs such as the Coal Quality Impact Model (CQIM™), the Coal Quality Information System (CQIS), and correlations from NOxPERT. It offers significant advances in assessing utility slagging and fouling issues by uniting other models developed under the CQE framework: SLAGGO and FOULER. The CCSEM approach offered by these tools allows greater confidence in modeling deposition phenomena through predictive capability in deposit growth, strength, and removability.

2.1 Object-Oriented Design

CQE has been developed using currently accepted object-oriented programming techniques using the C++ languages and standards. Objects (also called object types or classes) are defined to promote efficiency in developing and maintaining the CQE program and allow it to be easily modified in the future. The object-oriented techniques employed are based on the following principles:

- Encapsulation. Within CQE, each object or program module interacts with other modules via predefined "messages." These messages focus on the communication of data or knowledge to and from other objects. Encapsulation promotes effective management of data. That is, the internal representation of the data within the appropriate object is private, and hence, unavailable to manipulation by other program modules. This ensures that all access to data is via messages and, hence, provides for the opportunity to modify or expand object capability in the future without the need to be concerned with other object interaction (so long as current messages are supported and additional messaging is not required).

- Inheritance. Inheritance relates to the ability of an object to inherit the characteristics and procedures of another class and combine these with more specialized capabilities. In CQE, inheritance is used to provide the low-level common functionality required throughout objects (e.g., the ability to pass and receive messages, interface with files and user interfaces). Inheritance can also be used to develop "utility-specific" equipment performance, specialized versions of CQE base analysis and equipment classes, or costing modules (objects) by modifying already existing objects of similar functionality, or allow for future expansion by developing other specialized objects as appropriate.

- Polymorphism. This capability is closely associated with inheritance. Polymorphism allows the program to send messages to various classes of objects (related via inheritance) without explicit knowledge of the class to which the object actually belongs. This is a critical design consideration; polymorphism allows for specialized objects such as utility-specific equipment or costing modules to be treated as one of CQE's base class of objects. This capability greatly facilitates development of these specific objects and expansion of CQE in the future.

Effective object-oriented software design emphasizes effective design of the component objects. More precisely, a successful object-oriented design promotes the reuse of objects to solve different or new and unique problems by applying existing object functionality toward new solutions (via different sequences and the application of various object methods). Hence, the CQE design promotes both a strong object-oriented framework and a collection of independently designed, powerful classes of objects.

2.2 Hardware, Software and Operating System Requirements

System requirements include a combination of hardware and software specification that are discussed in this section. Although CQE was designed for OS/2 Version 2.0, the preferred operating system is OS/2 Warp (Version 3 or later). In addition, the user will need Watcom SQL for OS/2 Version 4.0 or higher (Watcom International Corporation, Waterloo, Ontario, Canada). CQE can run stand-alone on a single machine, or on a Banyan Vines network. Network operation will require a Watcom SQL Network Server for OS/2 and IBM's Transport Control Protocol/

Internet Protocol (TCP/IP) in addition to OS/2 and Watcom SQL on each client machine.

Hardware requirements (for stand-alone or client machines) are listed in Table 2-1.

Table 2-1
Hardware Requirements

	Minimum	Preferred
Hardware	486 PC, 33 MHz	Pentium PC, Market Clock Speed
RAM	16 MB	32 MB or greater
Disk Memory	200 MB	1 GB
Monitor	SVGA Color	SVGA Color
Graphics Card	Capable of 1024x768 Mode	Capable of 1024x768 Mode
External Drives	1.44 MB 3.5-inch; CD Rom	1.44 MB 3.5-inch; CD Rom
Mouse	Required	Required
Keyboard	Required	Required
Printer	Access to High-Speed Printer	Access to Laser Printer

2.3 Functional Capabilities

A user-friendly interface enhanced by extensive use of graphical tools collects and presents data within a powerful application framework and allows CQE to fulfill specific needs with different processes. This section discusses the tools that provide CQE's flexibility.

2.3.1 Applications

An Application guides users through an analysis by identifying the order in which activities should be performed and the information needed to successfully complete the analysis. Users can visually determine location within the analysis at all times by viewing a roadmap of the Application (Figure 2-1). The roadmap provides the user with the decision framework of the Application currently executed.

The user is able to visually determine location within the analysis at all times by viewing the roadmap of the Application. The roadmap provides the user with the decision framework of the Application that is being executed. The roadmap will be persistent in nature and will contain knowledge of the state of the Application: what has been done to date, what has been selected, and what goal is attempting to be accomplished. Each of the icons (bitmaps) shown in the roadmap represents a subapplication. These subapplications can be viewed in more detail when the user double-clicks on the desired icon. The detailed view of the subapplication will be similar in concept to the roadmap for the major Application. Color schemes and other means are used to inform the user about the status of the application.

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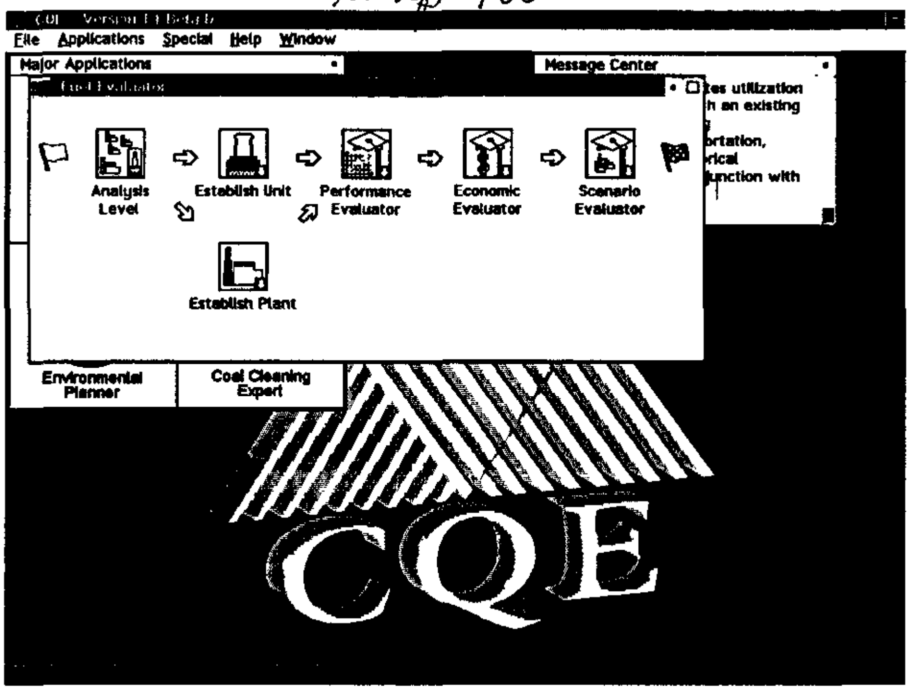


Figure 2-1
CQE Application Roadmap

Roadmaps for subapplications provide directions the user must follow such that the proper information is requested/supplied and the correct messages are passed to "objects" so that proper actions are taken. Of course, there may also be some direct interaction with specialized CQE experts/objects at the Application level. For each application, the user will be guided through the necessary steps, subapplications, and input screens necessary to complete the analysis. The user can stop along the way and view appropriate results, reexecute sections, reselect units or fuels to be evaluated, and continue (reiterating if necessary) until the analysis is complete. Applications can be stored and retrieved from disk like any other important data that the user wishes to store permanently. For user convenience and remembrance sake, the roads or paths the user takes throughout the major applications and the steps or actions the user has completed are denoted by a unique color scheme. The colors listed in Table 2-2 are used for each of the icons shown on the roadmap. Through this application framework, the user will be able to solve several specific problems in a logical and effective manner.

Table 2-2
Color Codes for Applications

Color	Action/Permissible
Green	Criteria met; user can access activity.
Blue	Criteria met; activity complete. Indicates user has already performed this step successfully, but the user can return to this entry
Orange	Same as blue, but user cannot return.
Red	Criteria not met; user cannot access this item. An alternate path will be provided or made available if user persists.

A number of menu options provide the user with alternative methods for proceeding through an application:

- Expand. View the roadmap for the current subapplication and proceed step-by-step through its functions.
- Expand and Execute. View the roadmap and automatically proceed through the current application or subapplication.
- Execute. Automatically proceed through the current application or sub-application.

The CQE includes four applications: Fuel Evaluator, Environmental Planner, Coal Cleaning Expert, and Plant Engineer (Figure 2-2).

2.3.1.1 Fuel Evaluator. The Fuel Evaluator will seamlessly perform system, plant, and/or unit-level fuel quality economic and technical assessments. It is designed for users without significant technical backgrounds and for those primarily interested in economic results. Specific unit-fuel combinations can be identified from within the Fuel Evaluator and reused in other CQE applications. The target audience for the Fuel Evaluator is utility fuel procurement managers and engineers.

2.3.1.2 Environmental Planner. The Environmental Planner will provide access to the evaluation and presentation capabilities of the Acid Rain Advisor (ARA™). It will simplify the ARA's data entry by guiding the user through a process of using existing CQE data to develop ARA data files. The Environmental Planner will be used by utility Clean Air Act compliance teams and utility environmental engineers.

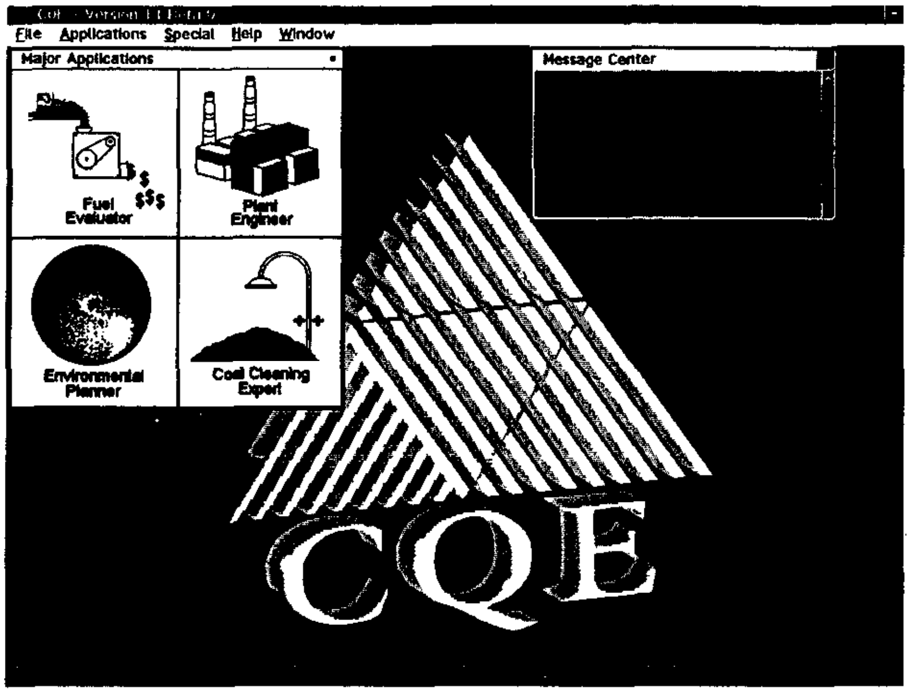


Figure 2-2
Major CQE Applications

2.3.1.3 Coal Cleaning Expert. The Coal Cleaning Expert will establish the feasibility of cleaning a coal, determine the appropriate cleaning process design, and predict associated capital costs for the selected process. The resulting cleaned coal product can be used as a fuel source in other CQE applications.

2.3.1.4 Plant Engineer. The Plant Engineer provides in-depth performance evaluations with a more focused scope than that provided by the Fuel Evaluator. Its detail will meet the needs of users who want to perform technical analyses on a few coals and evaluate alternate unit configurations. The Plant Engineer application was created for engineers and managers responsible for detailed assessments of plant performance under varying conditions.

2.3.2 Subapplications

Each Application is composed of several subapplications. A subapplication is a collection of objects that performs a specific function and is used by more than one Application. The following is a brief description of the generalized subapplications.

- Establish System/Plant/Unit. The Establish System (Establish Plant or Establish Unit) subapplication allows the user to identify the unit, fuel, load curve and unit/coal-specific performance overwrites to be evaluated. It incorporates the Select Plant/Unit, Unit Fuel Selector, and Establish Load Curve subapplications.

- Select Plant/Unit. This subapplication assists the user with creating or selecting specific plants, units, and equipment for evaluation. The Model Constructor can be accessed directly from the Plant/Unit Selector for defining additional configurations.

- Unit Fuel Selector. The Unit Fuel Selector subapplication allows the user to identify the fuels to be used in the evaluation. The fuels may be imported from CQIM or CQIS, selected from fuels currently contained in the database, specified by the user as a new fuel, or created as a blend of fuels contained in the database. A Fuel Search and Sort utility assists the user in identifying fuels from the database that meet certain criteria, such as heating value, ash or sulfur limits.

- Establish Load Curve. This subapplication assists the user in establishing an expected load curve for each unit. Load curves consist of hours per year at a given load, and can be generated based on unit usage (base, intermediate or peaking) and known hours of operation per year. Daily load profiles are also entered, for use in slagging and fouling predictive models.

- Performance Evaluator. The Performance Evaluator is used to identify performance calculational options, perform calculations and view results. It includes the Performance Calculator, which generates the plant, unit, or equipment performance results for a given set of parameters and coals, and the Interactive Output Utility (IOU), which displays pertinent performance results.

- Economic Evaluator. The Economic Evaluator is used to create or select economic data, perform economic calculations and view economic results. It includes the Economic Calculator, which performs economic calculations for a given set of parameters and coals, and the IOU, which displays the economic and performance results.

- Scenario Evaluator. The Scenario Evaluator subapplication allows the user to create and review several different user-specific analyses, or scenarios. A scenario includes appropriate unit/coal combinations to be used during the scenario evaluation. The Scenario Evaluator subapplication will perform system-level, plant-level, and unit-level scenario calculations by retrieving necessary and appropriate information from previously executed and existing data and present the results to the user from an overall scenario perspective.

2.3.3 User Interface

CQE deals with a large amount of data, using a number of specialized applications, so it is important that the interface to the program be user-friendly, yet sufficiently sophisticated to address each application's needs. The CQE user interface employs graphical screen elements such as windows, menus, and dialog boxes. These enable a vast amount of information to be displayed in a logical, consistent manner. To facilitate both ease-of-use and program flexibility, CQE features specific roadmaps to guide a user through an activity. In addition, icons and other graphical elements are used to further enhance the CQE interface. Tables, graphs, and other graphics round out the CQE user interface. This interface allows users to specify units and change key labels (on tables and charts) for custom configurations.

2.3.3.1 Model Constructor. The Model Constructor assists in building and editing plant, unit and equipment system models. It facilitates data entry and model setup, assists the user by identifying essential data and provides the ability to store and retrieve data. In addition, the Model Constructor provides the ability to import CQIM model files and the ability to copy unit configurations.

The CQE Model Constructor allows the user to build a visual representation of the plant being modeled. The user identifies the equipment systems at the unit or plant modeled and the flow paths or streams between these systems. The resulting "picture" allows the user to easily verify the accuracy of the model configuration. As the picture is being developed, equipment systems portrayed can be moved around the screen without losing stream connectivity (Figure 2-3). If an equipment system is deleted, the associated flow streams are automatically removed. The model constructor graphics also provide convenient access to data entry notebooks associated with each equipment system.

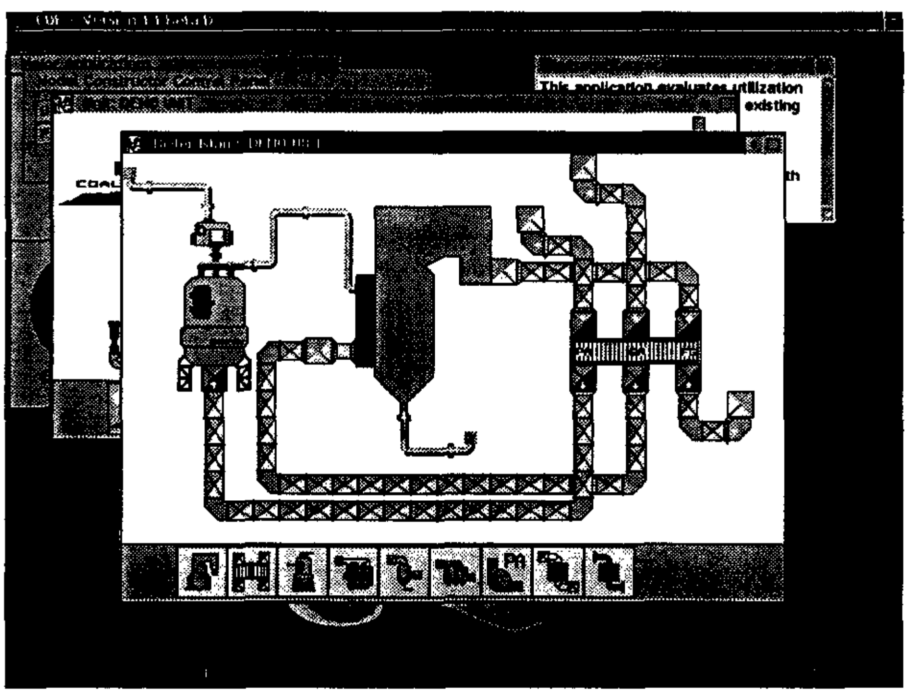


Figure 2-3
CQE Model Constructor Streams

Further graphical assistance is provided by the boiler diagram, which presents a scaled view of the steam generator model under construction and access to data entry notebooks (Figure 2-4).

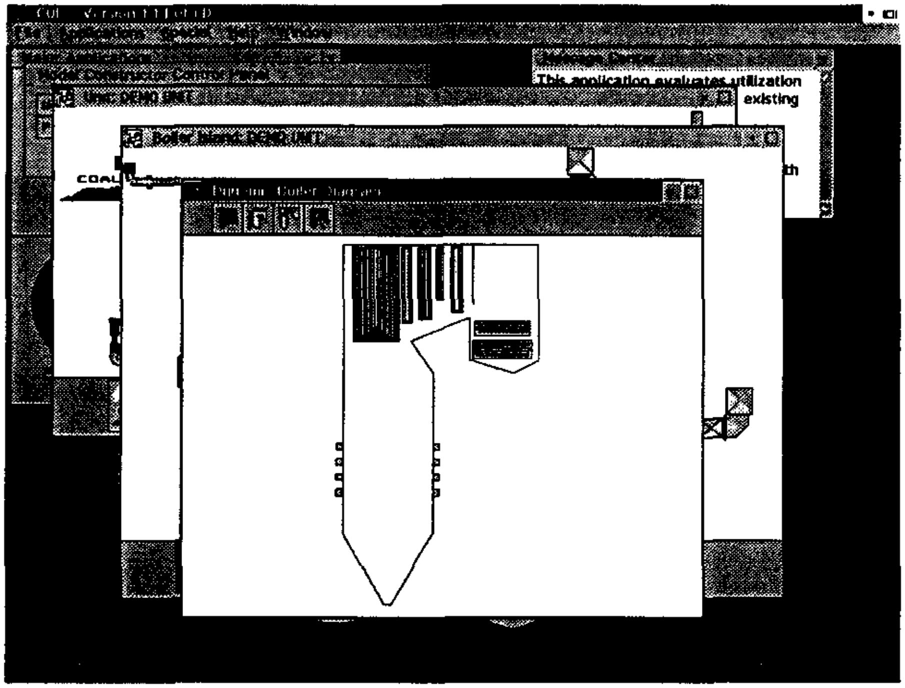


Figure 2-4
CQE Model Constructor Boiler Diagram

2.3.3.2 Interactive Output Utility. CQE output is presented in an Interactive Output Utility. The IOU presents calculational results in tables and graphs selected by the user (Figure 2-5). Equipment system level performance results and data inputs are presented in notebooks. The IOUs also provide hardcopy output and data export to spreadsheets via Dynamic Data Exchange links.

2.3.4 Data Storage

CQE incorporates a large amount of complex data. Some of this data is used internally, for example to store the user's position within an application or the results of a calculational evaluation. However, a user may wish to access or share other data such as coal quality information. To accommodate data accessibility, both object and relational database formats are used. These databases provide central data storage and concurrent user access.

2.3.4.1 Object Database Management System. To facilitate handling data specific to CQE, a commercially available object database management system ONTOS (ONTOS, Inc., Burlington, MA) is used. ONTOS allows CQE to easily and efficiently store and manage its information. ONTOS also allows CQE to take advantage of traditional database features such as concurrency control, client-server architecture, referential integrity, and database recovery.

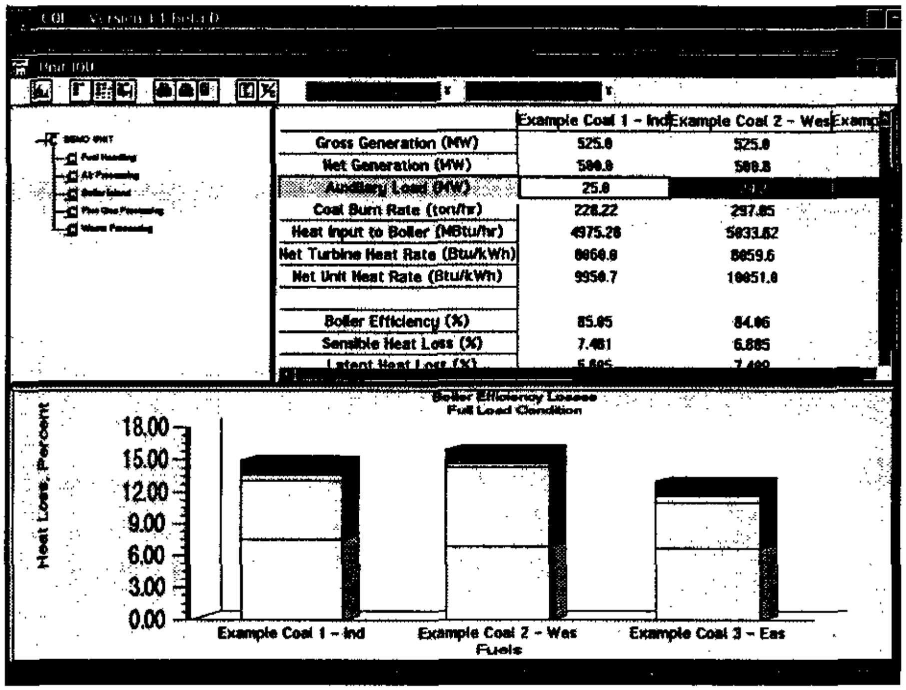


Figure 2-5
CQE Interactive Output Utility

2.3.4.2 Relational Database. A Watcom SQL relational database provides access to information that may be used external to CQE. This information includes fuel, load curve and economic data. This data can be accessed by external tools using the Transport Control Protocol/Internet Protocol (TCP/IP).

2.3.5 Help Facilities

CQE Help Facilities include status bar help text and context-sensitive help in critical areas. Hooks allow future inclusion of field-specific help and range checks.

2.3.6 Security

User access profiles will determine user privilege levels. Users can be assigned to a predefined category by the utility System Administrator. These categories limit access to sensitive information such as fuel prices and prevent accidental overwrite of key information such as unit configuration files.

2.4 Technical Models

CQE utilizes the CQIM code to evaluate performance for the coal handling, air heater, fans, pulverizer, bottom ash, economizer ash, precipitator ash and waste disposal systems. CQIM code is also used to perform maintenance/availability, derate, sensitivity and economic analyses. These capabilities are documented in detail in the CQIM Theory and User Manuals.

In addition to the unit performance and economic calculational capabilities, the CQE models coal cleaning, blending, and transportation. These capabilities are discussed further in the Coal Cleaning Expert and Unit Fuel Selector sections.

2.4.1 Boiler Expert

Within the CQE project, boiler performance modeling has been expanded beyond CQIM capabilities to interface with and use results from SLAGGO and FOULER models, developed by PSI PowerServe and UNDEERC.

2.4.1.1 Slagging Expert (SLAGGO). SLAGGO simulates the entire cycle of ash formation, deposit initiation, growth and removal processes based on coal properties, boiler design and boiler operation parameters. It predicts cleanliness factors as a function of furnace location. The boiler model provides boiler data to SLAGGO and uses results to evaluate the effect on overall boiler performance and economics. SLAGGO output is available to the user in the form of an ASCII text file.

SLAGGO has several components to simulate the entire cycle of ash deposit initiation, growth, and removal. The first component of SLAGGO--the ash formation model (AFM)--starts with the CCSEM coal and mineral data from baseline and test coals and uses the data to calculate the final ash particle size and composition distributions (PSCD). CCSEM (computer controlled scanning electron microscopy) coal and mineral analysis uses electron microscopy and energy dispersive X-ray spectroscopy to identify the mineral form of individual particles in a coal sample. In addition to compositional data, particle size data is obtained as well. The information on each particle is then aggregated to provide a profile of the mineral matter in the coal.

The second component of SLAGGO--the ash transport model (ATM)--calculates the ash flux transported to the waterwall surfaces by turbulent diffusion. The third component of SLAGGO--the deposit growth model (DGM)-- allows the growth of ash deposit on waterwalls and keeps track of its growth rate and monitors the porosity change. The thermal properties model (TPM) provides the DGM with the thermal properties for ash deposits, such as thermal conductivities and emissivities at different thermal conditions. The last component of SLAGGO, the deposit removal model (DRM), simulates the removal of ash deposit by sootblowing and determines the deposit removability from the estimated deposit strength.

The models communicate with the SLAGGO navigator. The Navigator accepts all the necessary inputs from CQE and gives back a cleanliness factor as a function of the furnace location and time. The Navigator also communicates with models of SLAGGO such as the AFM, the ATM, the DGM, and the TPM.

The AFM has several submodels: mineral matter transformation code (MMT); a preprocessor that renders MMT applicable to cyclone combustors, the alkali vaporization model (ALKAVAP); and excluded pyrite kinetics model (PYRKIN). The executable AFM was compiled using a 32-bit Fortran compiler (Watcom Fortran 77/386). There are two modes to run the code, a coarse resolution and a fine resolution version. The codes take 1 to 2 min to run on a 33 MHz 486 with 8 MB RAM, when using the coarse resolution option. The fine resolution option, which produces somewhat better results, takes 2 to 4 min to run.

The first step in the prediction of the effects of ash deposition on boiler operation is the identification of the size and chemical composition of ash particles formed during the coal combustion process. To accomplish this, PSIT employed a fundamentally-based MMT initially developed under DOE funding. Model refinements including technical improvements and adaptability to CQE have been accomplished to produce the final version of the AFM.

MMT takes as input the mineral analysis data of a given coal, follows the transformation process of coal mineral matter during combustion, and produces as output the ash data required for the prediction of slagging. ALKAVAP takes as input the ASTM ash analysis data, the temperature and the oxygen composition in the burner zone, and calculates the vaporized fractions of alkali (sodium and potassium) and alkaline earth (calcium) metals as oxides. The output is used through the navigator for the fouling prediction model of UNDEERC, FOULER. The inputs for PYRKIN are the size distribution of the excluded pyrites as produced from MMT and the temperature and the oxygen composition in the burner zone. The output is the time that a melt phase appears in an excluded pyrite particle of a given size and the time that it disappears due to iron oxide crystallization. These times are reported for all the excluded particles in the size distribution and are used by the DGM.

The ATM accounts for aerodynamics in wall-fired, T-fired, and cyclone furnaces. Although it is desirable to put the effects of low-NO_x burners in the model separately, this innovation was beyond the time and budget constraints of the program. Accounting for the differences in the transport phenomena with various low-NO_x combustion systems requires detailed knowledge of the design and operation of specific burners and overfire airports, and a technique to calculate differences in the nearfield aerodynamic behavior. This subject should be investigated in later versions of the CQE code.

With respect to slagging, there are two regions with differing transport mechanisms. These regions are the radiant region and the superheater tubes. The main transport mechanism for ash particles to the wall in the radiant zone is by turbulent diffusion; the main mechanism for the superheater tubes is inertial impaction.

The DGM describes three regimes: deposit initiation, growth, and maturation. Deposit initiation is caused by small ash particles that arrive by turbulent diffusion and adhere by van der Waals forces. Deposits grow by the arrival of sticky ash particles that adhere to the initial deposit. Deposits mature with time due to sintering of the ash particles within the deposit. The stickiness of ash particles arriving at waterwalls is determined by the viscosity model previously developed by PSIT. The viscosity model predicts particle viscosity at a given temperature from the composition of the individual ash particles. The strength of a deposit at a given time is determined from the density of the deposit calculated by the sintering rate of spherical ash particles.

The primary goal of the DGM is to predict the change of the cleanliness factor with time at five different regions of a furnace. Cleanliness factor has been defined as the ratio of the heat transmitted across the waterwall tubes with deposit on them to the heat transmitted across the "clean" waterwall tubes. The cleanliness factor decreases with time until it reaches an equilibrium value and reflects the effect of slagging on boiler performance. The cleanliness factor can be used to estimate the optimal sootblowing frequencies for economical operations. Because the DGM keeps track of the porosity change of the initial layer, it also sets the basis for the deposit strength and relates deposit strength to deposit removability by sootblowing.

The DGM needs the thermal properties of the ash deposit, such as thermal conductivities and emissivities, under different deposit conditions. The TPM gives the thermal properties at various deposit temperatures and deposit densities, which vary with time. The DGM and the TPM have been verified against the Fireside Performance Test Facility (FPTF) data provided by ABB Combustion Engineering Systems (ABB/CE).

The DRM simulates the deposit removal by sootblowers. The sootblower efficiency is first determined from the performance data provided by users for the baseline coals. The sootblower characterization curve thus determined as well as the deposit strength from the DGM are used to predict its removability. Change of cleanliness factor with the sootblowing is determined as the final output.

2.4.1.2 Fouling Expert (FOULER). FOULER predicts convective pass fouling based on boiler design, temperature and gas distributions, ash size and composition distributions and sootblowing and load drop parameters. The thermal resistivity of each heat exchange section is returned to the boiler model for calculation of the new temperature profile in the boiler. A cleanliness factor is then calculated for each heat exchange section from the difference in heat transfer between dirty and clean state of the tubes. A sootblower effectiveness curve is then developed as the amount of deposit that will be removed depending on the time interval between sootblowing cycles. FOULER output is available to the user in the form of an ASCII text file.

2.4.2 NOxPERT Derived Model

A NO_x prediction model based on NOXPERT Version 1.0 is included in CQE. This model predicts NO_x in parts per million based on coal parameters, operating data and furnace type.

2.4.3 Common System Evaluations

Equipment systems that serve more than one unit at a plant may be modeled at the plant level within CQE. Full load conditions for the common system are based on the requirements of each unit. Maximum equipment system demand, potential for derating, consumable rates, and auxiliary power consumption are determined for the system.

2.4.4 Acid Rain Advisor

The Acid Rain Advisor was developed as part of the CQE project. It is designed specifically to assist the user in managing Clean Air Act (CAA) compliance evaluations. By combining data collection and economic evaluation tools, the ARA can quantify costs and allowance needs associated with potential utility compliance strategies. ARA provides the means to rapidly select combinations of SO_2 reduction technologies at various units in a system, while simultaneously viewing system-wide results.

The Acid Rain Advisor helps manage both current and future planning needs. Costs and emissions reduction potential for selected SO_2 reduction alternatives can be considered in light of the utility's broader response to CAA issues. These concerns can be modeled by constructing different ARA scenarios to explore the relative merits and risks associated with such strategies. ARA "What-If" capabilities can quantify uncertainties in baseline assumptions and ramifications of future variations in market conditions.

The ARA can be used stand-alone, in conjunction with CQIM or within CQE. Within CQE it is accessed via the Environmental Planner. The ARA is documented in a separate User's Manual.

2.5 User Documentation

User support for CQE is documented in an on-line user's manual. The user's manual is contained on the same CD-ROM that is used to load the program. Written in Adobe Acrobat, the user's manual provides a hypertext description of the hardware and software requirements, help on the major applications, and a description of the process of running the model.

2.6 CQE EXAMPLE

CQE is designed to assist the user in performing a series of evaluations of the impacts of fuel choices on the overall cost of generation. The first step in performing this evaluation is to construct a model of existing power plants. Each plant consists of a number of separate units, and systems common to more than one unit. In the following example, a demonstration unit is used in the evaluation of three coals: a typical eastern high sulfur coal, an Illinois basin coal, and a Powder River basin coal.

The demonstration unit is a 500 MWe tangentially-fired balanced-draft unit. The unit has a cold-side electrostatic precipitator; the unit does not have flue gas desulfurization.

2.6.1 Constructing a unit model

When the user begins constructing a new unit model, the first screen that is displayed is a general-level screen of the major plant systems. These systems are fuel handling, air handling, the boiler island, flue gas treatment, and waste handling (Figure 2-6). When the user clicks on each of these systems, another screen appears for the more detailed input for that system.

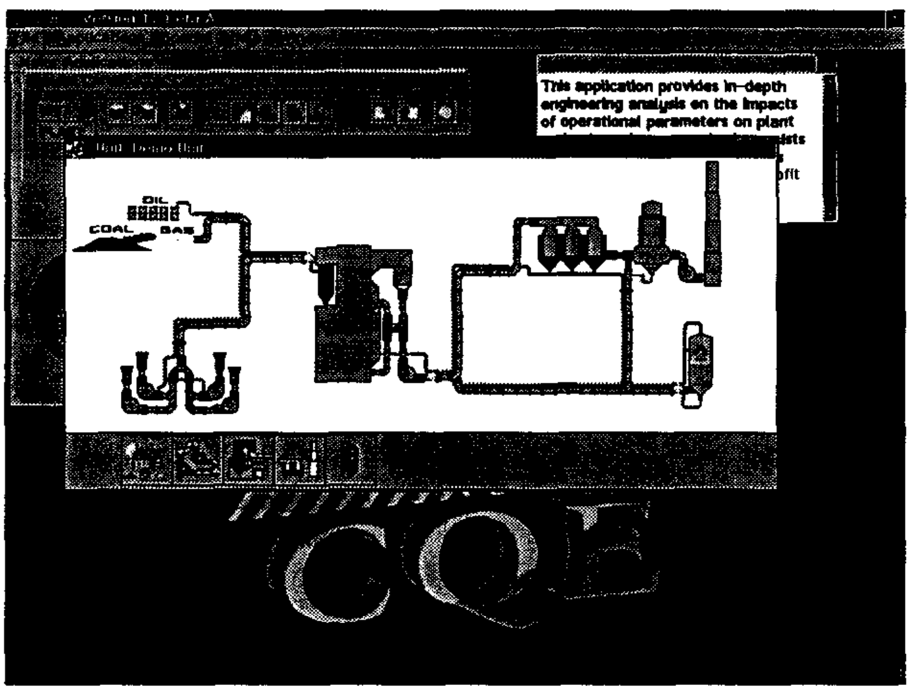


Figure 2-6
CQE Model Constructor - Main Screen

In Figure 2-7, the user constructs a model of the fuel handling system for the plant. The system is constructed by clicking on the equipment icons on the bottom of the fuel handling window, dragging the equipment icon onto the screen, and connecting it to the other pieces of fuel handling equipment. The two furthest right equipment icons allow the user to either combine or split fuel streams.

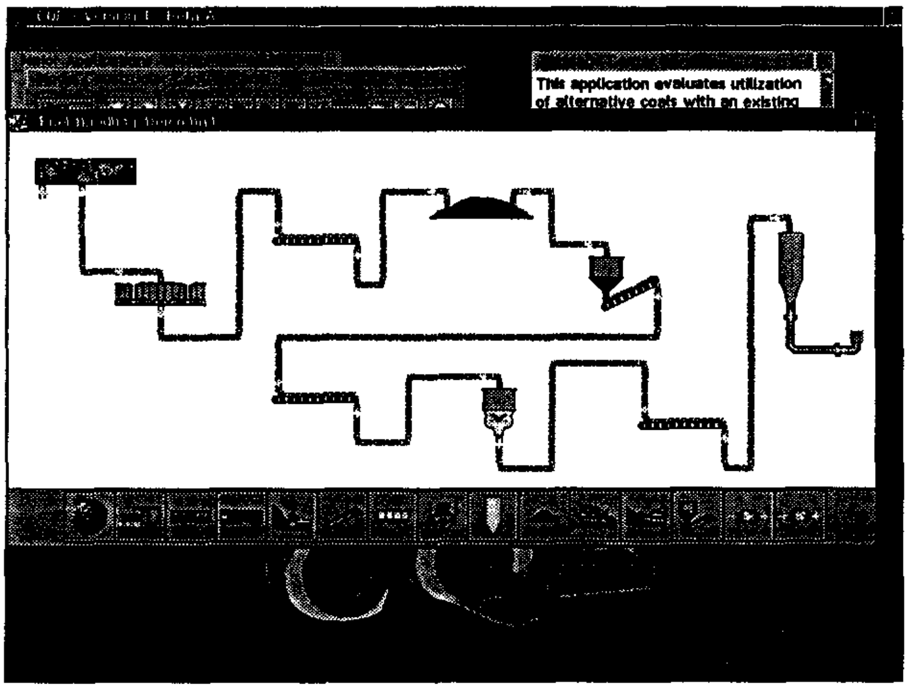


Figure 2-7
CQE Fuel Handling Screen

Figure 2-8 shows the construction of the air handling components of the unit model. An important feature to note are the two boxes at the end of the streams on the extreme right of the detail window. These are external connections to detail screens in other systems. These two external connections connect to the air heater in Figure 2-9.

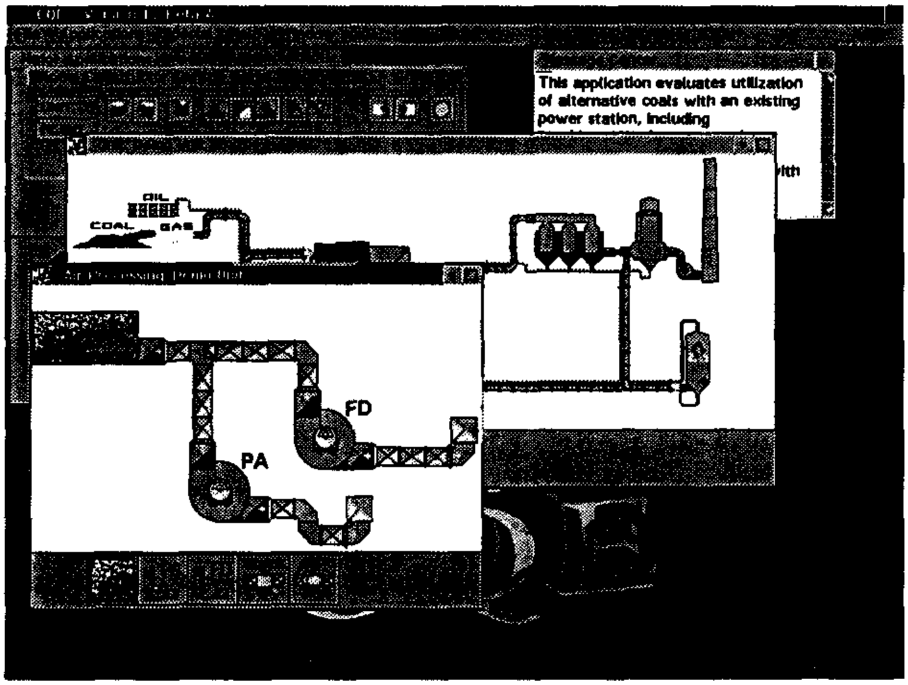


Figure 2-8
CQE Air Handling Screen

In Figure 2-9, the user inputs data for the boiler island, which includes the mills, air heater, and boiler. Another important feature to notice is the "black box" equipment icon. This allows the user to include in the unit model pieces of equipment that are not specifically modelled in CQE. The user employs the black box to perform an arithmetic function to a stream.

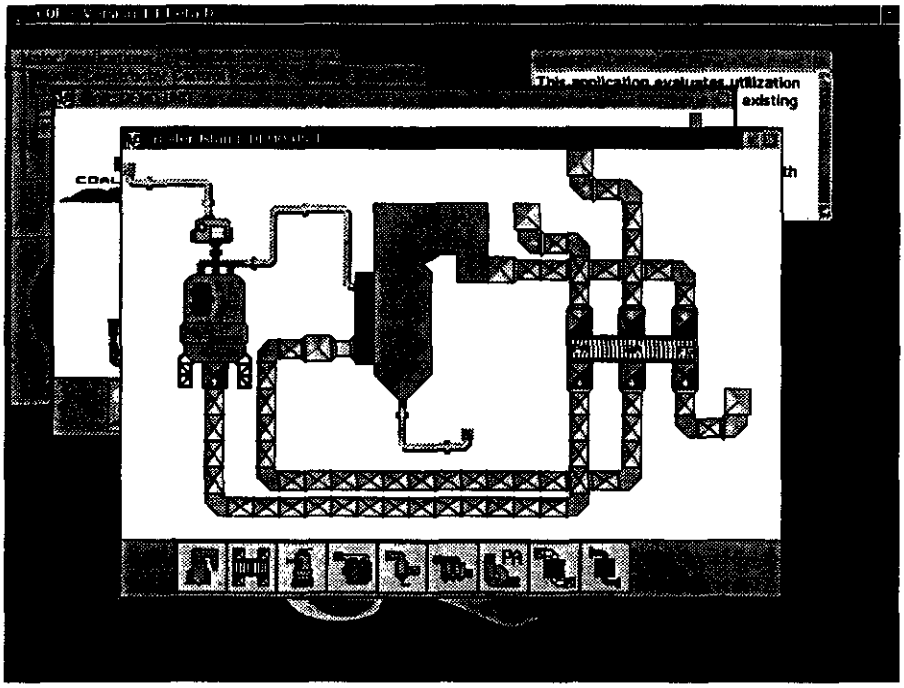


Figure 2-9
CQE Model Constructor - Boiler Island

If the user clicks on the boiler, another screen comes up where the user enters the detailed boiler design data (Figure 2-10). Finally, when the user clicks on each tube bank, a data input notebook appears (Figure 2-11). The notebook structure is used throughout CQE for data input screens, and provides a consistent organization to data input. Of particular note is that if the user clicks on the units for a given data point, a menu box comes up that allows the user to select from a variety of units, including metric units.

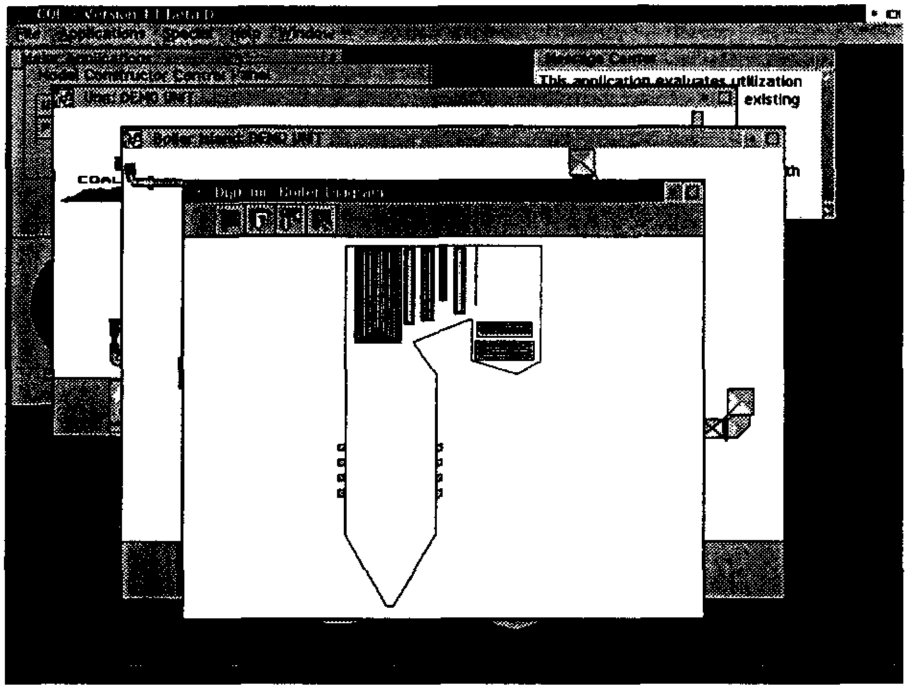


Figure 2-10
CQE Model Constructor - Boiler Section

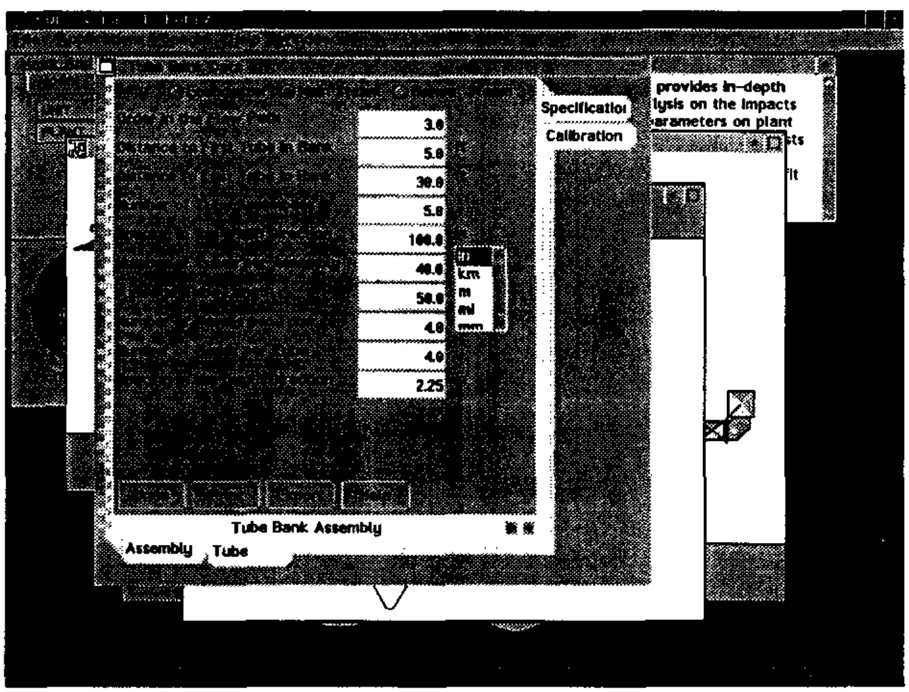


Figure 2-11
CQE Model Constructor - Data Input

When constructing the unit model, the user proceeds through the windows and notebooks until the data input is complete. In many cases, not all of the data that can be used in CQE is available. Fortunately, CQE has an extensive data defaulting capability, and often data that is unobtainable can be defaulted. In general, using real data is vastly superior to using defaulted data, because defaulted data can lead to CQE either predicting unit coal impacts that are not real, or not predicting impacts that are real. However, defaulted data can frequently be used if care and discretion are applied to the modelling and data interpretation. Once a unit model is constructed, the user can employ this unit model in the evaluation of the effects of various fuels in that unit.

2.6.2 An Example Fuel Evaluation

In CQE there are four major applications: the Fuel Evaluator, the Plant Engineer, Environmental Planner and Coal Cleaning Expert. The function of each of these is described above. In this example, three coals will be evaluated in the demonstration unit. The three coals are a eastern high sulfur coal, an Illinois basin coal, and a Powder River basin coal.

To perform this evaluation, one starts the Fuel Evaluator, and follows the green bordered boxes through the roadmap. In general, the steps are to select a unit, select a series of fuels to evaluate (a fuel list), select the unit annual load curve, and run the model (Figure 2-12).

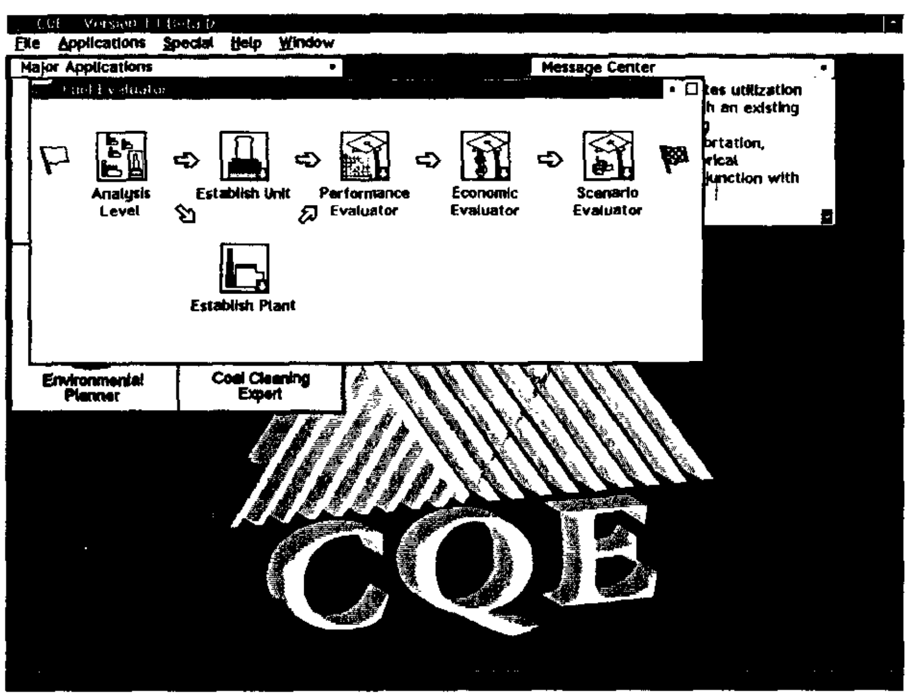


Figure 2-12
CQE Fuel Evaluator

As the model runs, default values that CQE uses as the program progress are displayed in a scrolling text box. These values can be printed to assist in evaluating the model results when the program execution is complete.

After program execution, the user runs a portion of the program called the Interactive Output Utility (Figure 2-13). This section of the program displays the technical results of the modelling. CQE differs from previous programs of this type in that the output features of CQE are highly flexible. Output of the performance of the unit can be displayed in a series of pre-defined tables, or, if the predefined tables do not give the results that the user is interested in, the user can construct and save a custom table of results. In addition, a graphical depiction of the results is available.

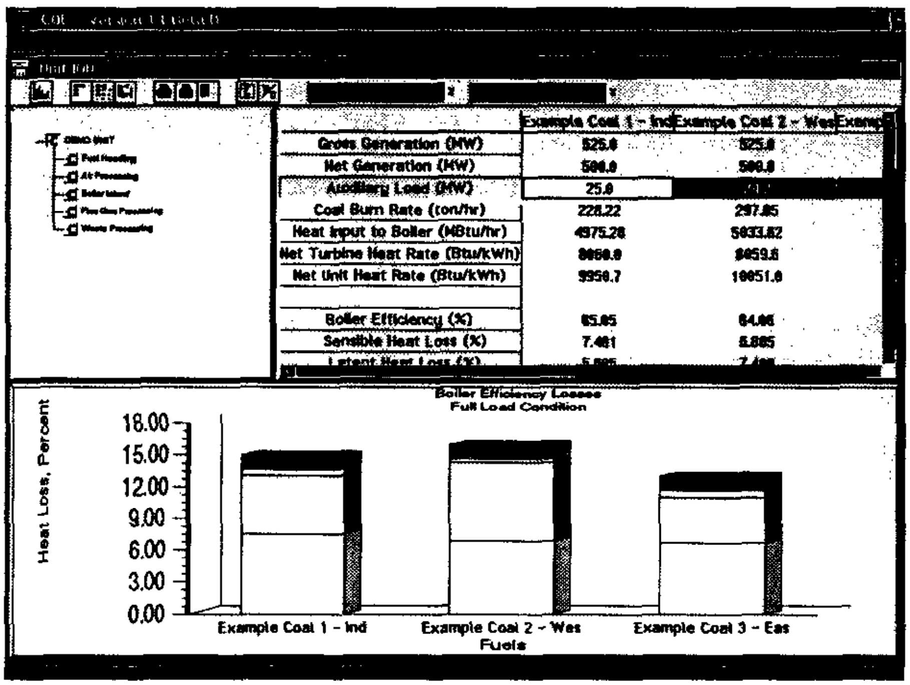


Figure 2-13
CQE Interactive Output Utility

In this case, the Powder River basin coal gave the lowest boiler efficiency, and hence the highest net unit heat rate. This is largely due to the higher moisture content of the low-rank coal. As a result, this coal required more air flow, and more coal flow for the same gross generation. The greater flows meant that equipment had to run harder, thus the auxiliary power was highest for the Powder River basin coal.

The technical performance of a given coal in a given unit is only half of the decision-making process in evaluating the use of that coal. The next step in running the Fuel Evaluator is to assess the economics of the use of that coal (Figure 2-14).

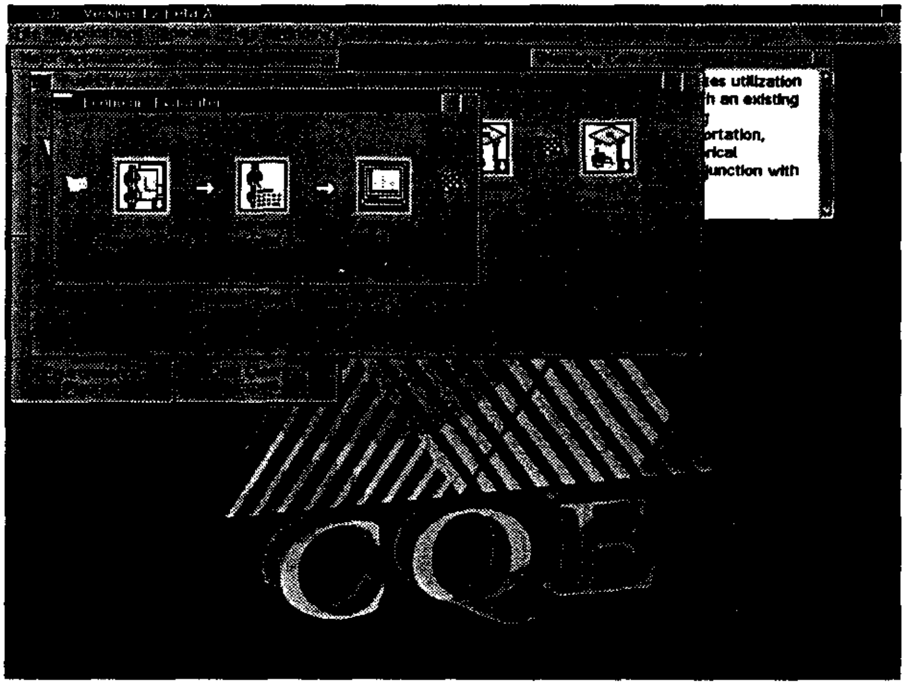


Figure 2-14
CQE Economic Evaluation

CQE allows the user to enter and store economics files the contain information used by CQE to put dollar values on the performance impacts that a coal has on a boiler. For example, if the technical model predicts a change in unit auxiliary power, the economic file tells CQE the value of a unit of auxiliary power, and the two together calculates the value of using a coal that saves auxiliary power to the power generating utility (Figure 2-15).

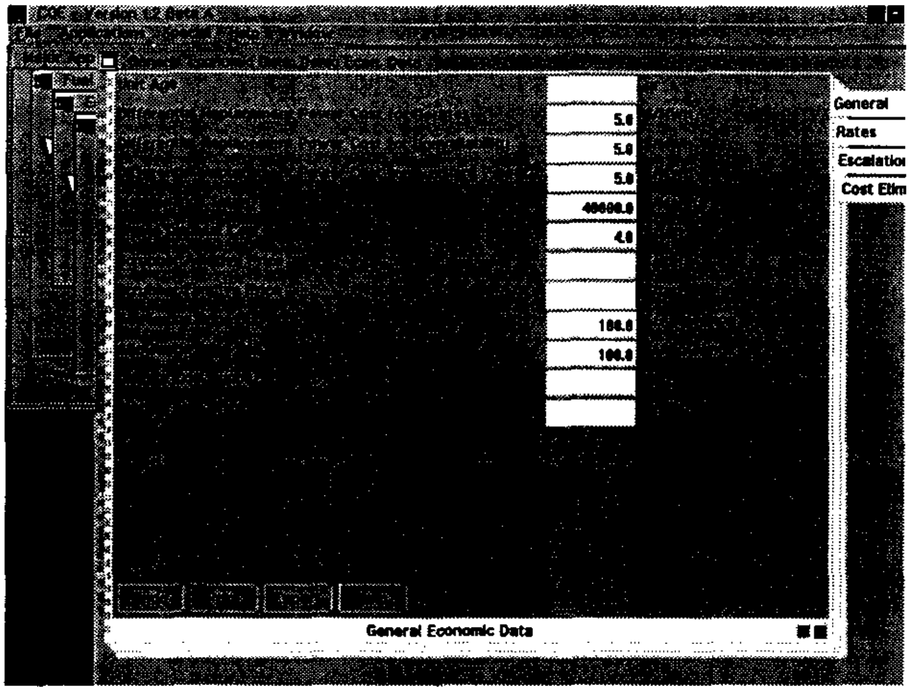


Figure 2-15
CQE Economic Evaluation - Data Entry

Similar values are applied to maintenance labor, unit availability, unit derates (if any), unit consumables (such as limestone if there is a scrubber), waste disposal, and sulfur emissions. These values are listed as differentials from the base coal.

To completely assess the use of one coal versus another, one must compare the total costs of generation for each coal. To arrive at this number, CQE sums the financial impacts of all of the operational effects of each coal (Figure 2-16). Ultimately, one can calculate the breakeven cost of each coal, that is, the price that each coal would cost to make the total cost of generation with that coal equal to the cost of generation with the current coal. If the purchase price of a given coal is greater than its breakeven cost, the coal should not be purchased. If it is less than its breakeven cost, then the coal is a wise purchase.

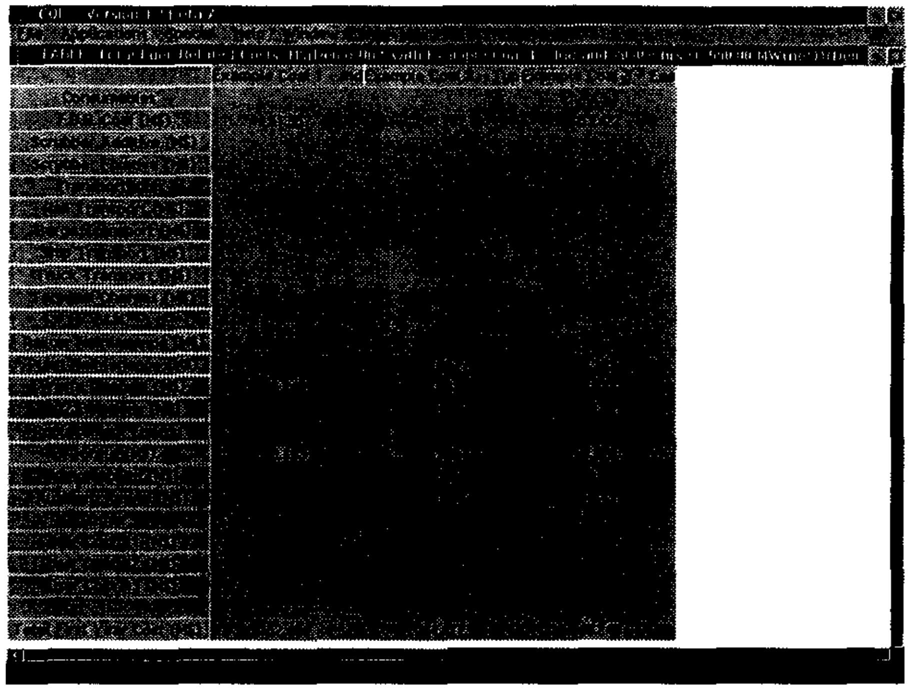


Figure 2-16
CQE Economic Evaluation - Generation Costs

In this case, in spite of the fact that the low-rank coal has poorer performance, the economics indicate that it is in fact the best fuel choice. The total fuel cost for the low-rank coal is lower than the other coals, and the sulfur emissions are less. These factors more than offset the increased plant maintenance costs, lost availability, and increased derate. CQE offers the user a tool to evaluate fuels based on their total impact on the economics of generating power.

3.0

CQE BETA TEST PROGRAM

Initial copies of CQE were released to beta testers in late June, 1995. In all, seven companies participated in the CQE beta test program. These companies were:

- CQ Inc., Homer City, Pennsylvania
- New York State Electric and Gas, Binghamton, New York
- Kansas City Power and Light, Kansas City, Missouri
- Houston Light and Power, Houston, Texas
- Duke Power, Charleston, North Carolina
- United Power Association, Elk River, Minnesota
- Electric Power Research Institute, Palo Alto, California

Because there was no automatic installation procedure written for CQE in the early stages of its development, each utility sent a computer capable of running CQE to Black & Veatch in Overland Park, Kansas, where the installation was performed.

Early versions of the beta-test CQE did not contain a number of features that ultimately were in the final release version of CQE. Some of the features added during the beta test program were the CCSEM slagging and fouling treatment, stream splitters, and black boxes. Stream splitters allow the user to divide or combine gas, air, coal or waste streams. Black boxes allow the user to perform an operation that modifies the properties of a stream. Black boxes are used in instances where CQE does not specifically model a particular arrangement or piece of equipment, and they allow the user to simulate the effect of that arrangement or equipment without building a sophisticated object model.

In all, five versions of CQE were issued during the beta test program, with the last version being released at the beginning of November 1995. Subsequent changes to the model were deferred until the final version, which was released in late December 1995.

Reports back to Black & Veatch during the beta test program were handled verbally; no complicated system of reporting was established. Feedback on CQE from beta testers focussed largely on "look and feel" issues, with changes being made to data entry screens, the "roadmaps," and the Model Constructor.

During the Beta test program, the users recognized the need for an additional status color for roadmap object borders. In addition to the aforementioned green, red, and blue, an additional status color of orange was established. This color was to indicate objects in the roadmaps that had already been performed, but that the user could return to if the user needed to change the way an application was progressing.

Final release of the program (Version 1.0) occurred in late December 1995; however, work continues on some features of the program. Version 1.1 Beta was released in June 1996, and the program has been improved in a number of significant aspects. First, the program is more robust, being more tolerant of erroneous user inputs. In addition, the treatment of CCSEM slagging and fouling data is more seamless, recognized bugs were fixed, and the code was streamlined to run faster.

4.0

DEMONSTRATION PROGRAM

To develop CQE, a demonstration program was conducted that developed baseline data and data for algorithm development and testing. The CQE demonstration program consisted of three activities:

- Coal characterizations that studied the physical and chemical properties of all components of thirteen coals. These studies provided baseline coal data for CQE, including the theoretical potentials for removing ash-forming, sulfur-bearing, and trace element-bearing minerals, and sometimes included commercial-scale cleaning evaluations to examine the extent to which coal quality can be improved using various coal cleaning techniques.

- Pilot-scale combustion tests that were conducted to support the coal characterization and field testing efforts. ABB Power Plant Laboratories Combustion Engineering, Inc. (ABB CE) conducted all pilot-scale combustion tests, with the exception of the cyclone boiler simulations, which were the responsibility of Babcock & Wilcox (B&W). Bench-scale tests were performed by ABB CE, B&W, and the University of North Dakota Energy and Environmental Research Center (UNDEERC).

- Boiler field tests that were vital in establishing correlations between field-, pilot-, and bench-scale testing. EPT (Electric Power Technologies), the Fossil Energy Research Corporation (FERCO), Energy and Environmental Research Corporation (EER), and Southern Research Institute (SoRI) conducted tests at six utility boilers.

Data from each of these activities was then used to develop CQE algorithms and models, and the utility boiler field test results were also correlated with CQIM predictions to aid in CQE development. Intermediate products were also developed during the course of this work: the Acid Rain Advisor and the Fireside Advisor.

4.1 Coal Characterizations

Between 1990 and 1992, CQ Inc. conducted thirteen detailed coal cleanability characterizations to provide baseline coal data for CQE. Coal cleanability characterizations involve extensive investigations of physical and chemical properties of all components of the coal and assessments of the theoretical potential for removing ash-forming, sulfur-bearing, and trace element-bearing minerals associated with the coal. In addition, coal cleanability characterizations often include commercial-scale cleaning evaluations to examine the practical extent to which coal quality may be improved using various coal cleaning techniques.

Coal characterizations were completed in conjunction with field combustion testing at:

- Public Service of Oklahoma's (PSO) Northeastern Station, Oologah, Oklahoma.
- Mississippi Power Company's (MPC) Jack Watson Station, Gulfport, Mississippi.
- Northern States Power Company's (NSP) Allen S. King Station, Bayport, Minnesota.
- Alabama Power Company's (APC) Gaston Station, Wilsonville, Alabama.

No coal characterizations were completed in conjunction with combustion testing at New England Power Company's Brayton Point Station.

4.1.1 PSO Northeastern Station Coals

In 1990, PSO provided approximately 500 tons of Croweburg Seam coal from Peabody Coal Company's Rogers County No. 2 Mine located near Vinita, Oklahoma, and about 100 tons of Wyodak Seam coal from Kerr McGee's Jacob's Ranch Mine located in Campbell County, Wyoming. A summary of raw coal qualities for these coals is shown in Table 4-1.

Based on analyses of this sample, Croweburg Seam coal is high volatile B/C bituminous in rank, containing lignitic-type ash and having sulfur dioxide emission potential under 1.2 lbs/MBtu. The ash fusion and chemical composition analyses indicate that this coal has a high slagging potential, but a relatively low fouling potential. In addition, the ash content in fine size fractions of the coal (nominal minus 200 mesh) is somewhat high (> 50 percent), indicating significant silicate and aluminosilicate mineral content.

Analyses of the Wyodak Seam coal from the Powder River Coal Basin in Wyoming show that it is subbituminous C in rank. This coal, naturally high in moisture and volatile matter content, usually contains only about 5 to 8 percent lignitic-class ash and less than 0.6 percent total sulfur as-mined. This sample of Wyodak Seam coal has a severe slagging potential and a low fouling potential.

Table 4-1
Raw Coal Quality Summary for Croweburg and Wyodak Seam Coals (Dry wt% basis analyses except where noted)

	Croweburg Seam Rogers County, OK	Wyodak Seam Campbell County, WY
Total Moisture (As-received) (Wt %)	9.42	31.63
Fixed Carbon (Wt %)	53.08	49.84
Volatile Matter (Wt %)	33.76	43.48
Ash (Wt %)	13.16	6.68
Higher Heating Value (Btu/lb)	12,672	11,919
Total Sulfur (Wt %)	0.69	0.54
Pyritic Sulfur (Wt %)	0.28	0.11
Organic Sulfur (Wt %)	0.40	0.41
SO_2 Emission Potential (lbs/MBtu)	1.09	0.91
Carbon (Wt %)	71.02	68.14
Hydrogen (Wt %)	4.41	4.94
Nitrogen (Wt %)	1.50	0.92
Oxygen (Wt %)	9.22	18.78
Chlorine (Wt %)	0.24	0.04
Hardgrove Grindability Index (HGI)	62	57
Ash Fusibility (Reducing/Oxidizing)		
Initial Deformation (°F)	2064/2147	1990/2170
Softening (°F)	2111/2207	2075/2215
Hemispherical (°F)	2149/2267	2079/2218
Fluid (°F)	2215/2357	2082/2226
Slagging Index (Classification)	2105 (High)	2036 (Severe)
Fouling Index (Classification)	0.64 (Low)	0.84 (Low)

Slagging Index Classification

Low	> 2450
Medium	2250 to 2450
High	2100 to 2250
Severe	< 2100

Fouling Index Classification

Low to Medium	< 3
High	3 to 6
Severe	> 6

4.1.1.1 Coal Cleanability and Liberation Assessments. The potential for improving the quality of Croweburg Seam coal using coal cleaning techniques is significant. Theoretically, cleaning can probably reduce the ash content of this coal by 50 percent and potential sulfur dioxide emissions by at least 25 percent at energy recovery levels exceeding 90 percent. As shown in Figure 4-1, liberation assessments --which involve crushing and separating samples of raw coal into various size and density fractions and analyzing the fractions for energy and impurity contents-- indicate that sulfur dioxide emissions may be reduced by as much as 35 percent if the coal is crushed prior to cleaning. The laboratory washability data on Wyodak Seam coal show that cleaning will probably improve its quality only slightly, however, since the coal is naturally low in ash and total sulfur content.

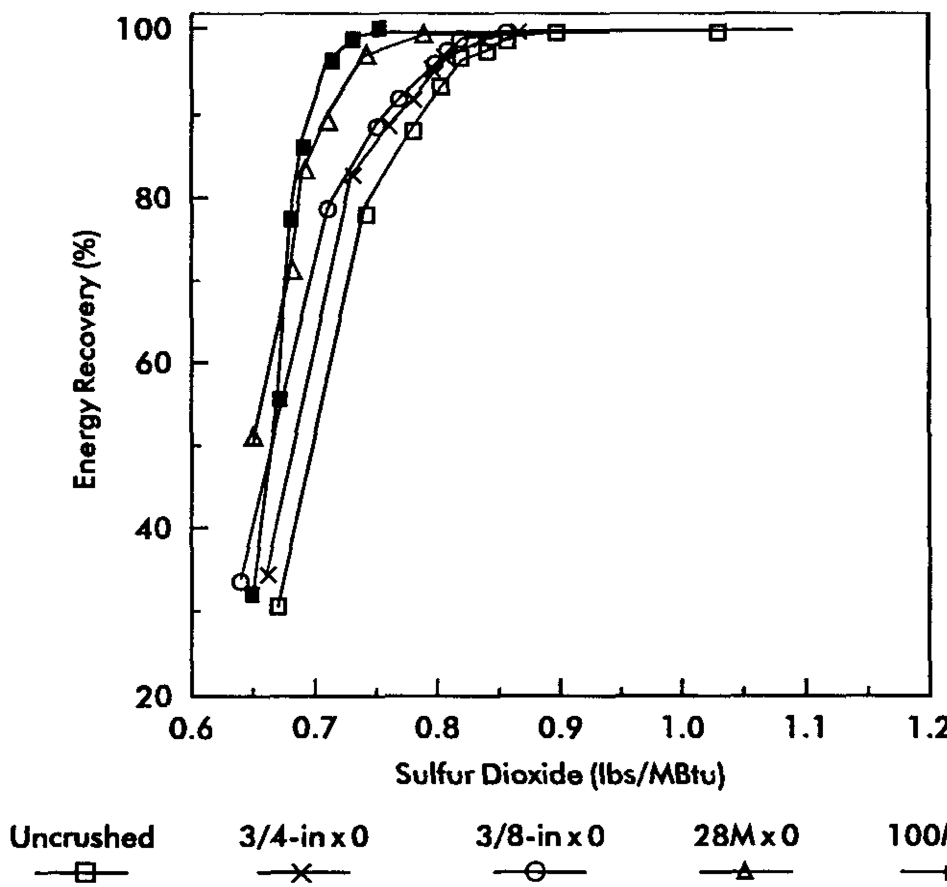


Figure 4-1
The Potential for Sulfur Dioxide Reduction During Cleaning of Uncrushed and Crushed Croweburg Seam Coal

4.1.1.2 Flowsheet Testing. To evaluate the effectiveness of coal cleaning at commercial scale to remove impurities from Croweburg Seam coal, CQ Inc. engineers and technicians conducted three flowsheet tests at CQ Inc.'s Coal Quality Development Center--a 25-tph, multi-configuration facility located in Homer City, Pennsylvania, containing equipment for receiving, storing, crushing, grinding, slurrying, cleaning, drying, and loading coal. The flowsheet used for these tests, shown in Figure 4-2, consisted of heavy-media cyclones to clean coarse-size coal, water-only cyclones to clean intermediate-size coal, and froth flotation to clean fine-size coal and ancillary sizing, pumping, dewatering, and handling equipment.

For all three tests, raw coal feed was crushed to minus ¾-inch topsize. Circulating specific gravity for the heavy-media cyclone was varied among the tests. Target gravities were 1.55, 1.40, and 1.80 for tests 1, 2, and 3, respectively. A summary of results for the three flowsheet tests is given in Tables 4-2 and 4-3.

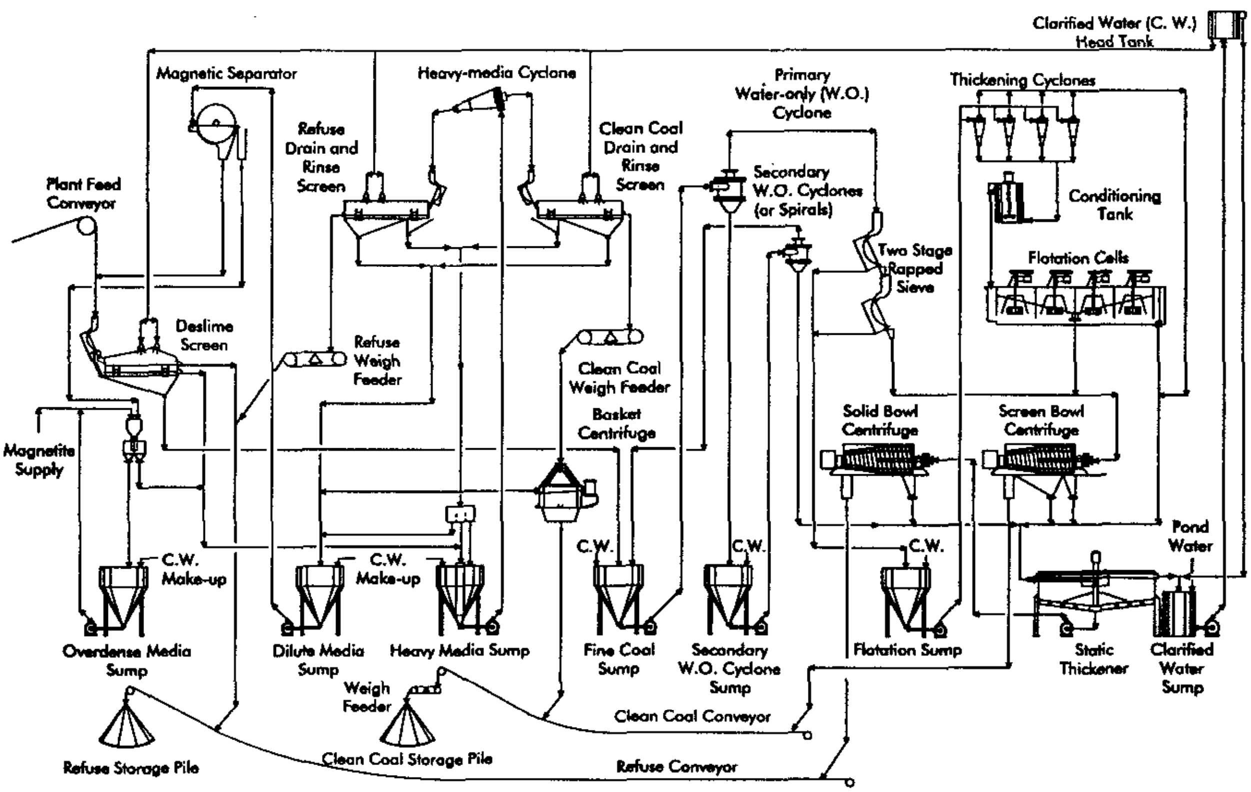


Figure 4-2
CQ Inc. Standard Flowsheet: Heavy-media Cyclone, Water-only Cyclone, Froth Flotation

As shown in Table 4-2, energy recovery exceeded 90 percent in each of the three flowsheet tests. Moreover, cleaning reduced the ash content and sulfur dioxide emission potential of Croweburg Seam coal by at least 50 and 15 percent, respectively, during each flowsheet test. Other coal quality characteristics of Croweburg Seam coal were also changed as a result of cleaning. For example, Table 4-3 shows that the ash fusion temperatures of the clean coal from Flowsheet test 2 are significantly higher than those of the raw coal and that the grindability of the clean coals is less than that of the raw coal.

Conversely, a comparison of several indices calculated from ash composition analyses shows that cleaning did not decrease the slagging or fouling potential of the Croweburg Seam coal appreciably during any of the flowsheet tests. However, pilot-scale combustion test data suggest that certain blends of clean Croweburg and raw Wyodak seam coals have a lower slagging potential than do blends of raw Croweburg and raw Wyodak seam coals.

Table 4-2
Flowsheet Performance Comparison: Croweburg Seam Coal, Rogers County, Oklahoma (Dry Basis)

	Raw Coal	Test 1 HMC/WOC/FF	Test 2 HMC/WOC/FF	Test 3 HMC/WOC/FF
COAL SIZE	1½-inch X 0	¾-inch X 0	¾-inch X 0	¾-inch X 0
ANALYSES				
Ash (Wt %)	13.16	6.63	4.84	6.74
Volatile Matter (Wt %)	33.76	35.16	37.53	35.49
Total Sulfur (Wt %)	0.69	0.62	0.62	0.65
Pyritic Sulfur (Wt %)	0.28	0.17	0.13	0.18
Pyritic Sulfur/Total Sulfur (%)	40.6	27.4	21.0	27.7
Higher Heating Value (Btu/lb)	12,672	13,854	14,168	13,728
Ash Loading (lbs/MBtu)	10.4	4.8	3.4	4.9
SO_2 Emission Potential (lbs/MBtu)	1.09	0.90	0.88	0.95
PERFORMANCE				
Yield (Wt %)	NA	82	80	87
Energy Recovery (%)	NA	91	90	95
Ash Reduction (Heat Unit Basis, %)	NA	54	67	53
SO_2 Reduction (Heat Unit Basis, %)	NA	24	28	20

HMC = Heavy-media Cyclone WOC = 2-Stage Water-only Cyclone FF = Froth Flotation
NA = Not Applicable

Table 4-3
Combustion Parameters Comparison: Croweburg Seam Coal, Rogers County, Oklahoma (Dry Basis, except HGI)

	Raw Coal	Test 1 HMC/WOC/FF	Test 2 HMC/WOC/FF	Test 3 HMC/WOC/FF
ULTIMATE ANALYSIS				
Carbon (Wt %)	71.02	69.18	79.39	76.75
Hydrogen (Wt %)	4.41	4.91	5.06	4.90
Nitrogen (Wt %)	1.50	1.95	1.91	1.71
Oxygen (Wt %)	9.22	7.45	8.18	9.25
CHLORINE (Wt %)	0.24	0.18	0.25	0.19
GRINDABILITY (HGI)	62	57	58	56
ASH FUSIBILITY (°F) (Reducing/Oxidizing)				
Initial Deformation	2064/2147	2068/2254	2164/2289	2091/2121
Softening	2111/2207	2163/2293	2233/2331	2118/2178
Hemispherical	2149/2267	2191/2348	2283/2425	2136/2197
Fluid	2215/2357	2218/2382	2422/2510	2160/2291
CALCULATED INDICES				
Silica Percentage	62	65	74	62
Base-to-Acid Ratio	0.51	0.43	0.31	0.49
Slagging Index (Classification)	2105 (High)	2124 (High)	2216 (High)	2112 (High)
Fouling Index (Classification)	0.67 (Low)	0.52 (Low)	0.56 (Low)	0.36 (Low)

HMC = Heavy-media Cyclone WOC = 2-Stage Water-only Cyclone FF = Froth Flotation

Slagging Index Classification

Low	> 2450
Medium	2250 to 2450
High	2100 to 2250
Severe	< 2100

Fouling Index Classification

Low to Medium	< 3
High	3 to 6
Severe	> 6

4.1.1.3 Trace Element Reduction During Coal Cleaning. Although the Clean Air Act Amendments of 1990 do not impose limits on air toxics emissions from power plants that fire fossil fuels containing trace amounts of metal elements, future regulations are expected to be implemented at the conclusion of a federally-mandated emissions study that is in progress. Because of the uncertainty of the full effects of any such new laws, CQE coal characterization studies included evaluations of the potential of using physical coal cleaning techniques to remove trace elements of concern.

Test data summarized in Figure 4-3 show that cleaning reduces the concentration of many trace elements found in Croweburg Seam coal. Moreover, these data indicate that the degree of cleaning intensity (as indicated by different circulating specific gravities for the heavy-media cyclone) affects the level of trace element removal during coal cleaning.

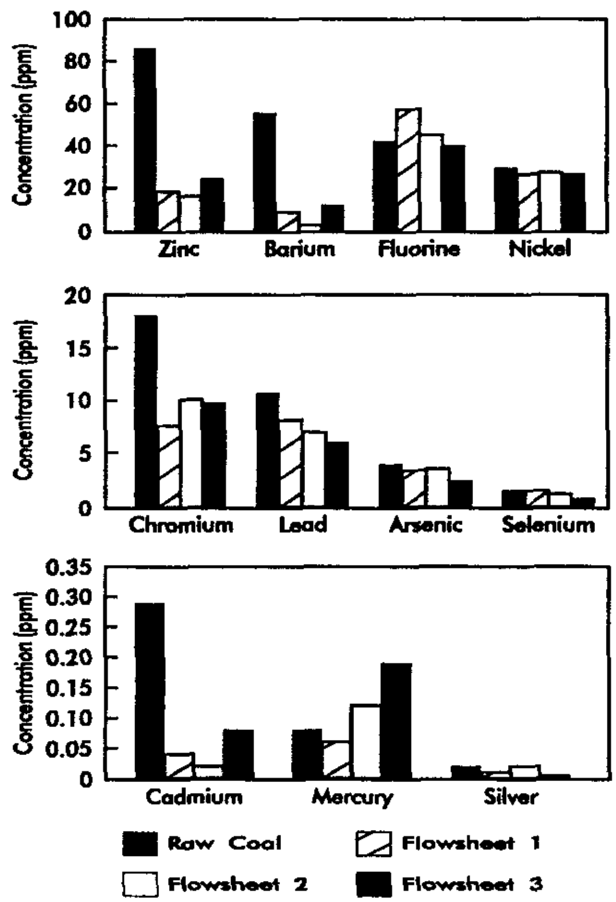


Figure 4-3
Trace Element Concentrations in Raw and Clean Croweburg Seam Coal

4.1.2 MPC Watson Station Coals

In late 1990 and early 1991, CQ Inc. engineers completed coal cleanability characterizations on four coals that were used in field combustion tests conducted at Mississippi Power Company's Jack Watson Station, in Gulfport, Mississippi. Jader Fuel Company provided 150 tons each of Illinois No. 2, No. 3, and No. 5 seam coals from its Jader No. 4 Mine in Gallatin County, Illinois; and Island Creek Coal Company donated 250 tons of West Kentucky No. 11 Seam coal from its Ohio No. 11 Mine in Union County, Kentucky. A blend of cleaned Illinois coals was used as the baseline fuel in the field combustion tests, while a cleaned West Kentucky No. 11 Seam coal was used as the alternate fuel.

4.1.2.1 Raw Coal Quality. A summary of the raw coal quality of the Illinois Basin coals is shown in Tables 4-4 and 4-5. Based on these analyses, the three Illinois coals are high volatile A bituminous in rank and the Kentucky coal is high volatile C bituminous in rank. Raw coal characterization analyses indicate that the West Kentucky No. 11 Seam coal has a medium slagging index, the Illinois No. 3 Seam has a high slagging index, and the Illinois No. 2 and No. 5 seam coals have severe slagging indices. A low fouling index is indicated for the Illinois No. 2 and No. 3 seam coals and medium fouling indices are indicated for the Illinois No. 5 and Kentucky No. 11 seam coals. As mined, all of these coals have very high ash loading and SO_2 emission potentials.

Table 4-4
Raw Coal Analysis Comparison: Illinois No. 2, No. 3, and No. 5 Seam Coals, Gallatin County, Illinois and West Kentucky No. 11 Seam Coal, Union County, Kentucky (Dry Basis)

	Illinois No. 2 Raw Coal	Illinois No. 3 Raw Coal	Illinois No. 5 Raw Coal	West Kentucky No. 11 Raw Coal
ANALYSES				
Ash (Wt %)	14.45	20.73	16.83	35.42
Volatile Matter (Wt %)	33.83	32.73	35.04	29.10
Total Sulfur (Wt %)	5.27	4.25	4.74	3.78
Pyritic Sulfur (Wt %)	3.64	2.73	2.96	1.99
Pyritic Sulfur/Total Sulfur (%)	69.1	64.2	62.4	52.6
Higher Heating Value (Btu/lb)	12,766	11,596	12,194	9,022
Ash Loading (lbs/MBtu)	11.3	17.9	13.8	39.3
SO_2 Emission Potential (lbs/MBtu)	8.26	7.33	7.77	8.38

Table 4-5
Raw Coal Combustion Parameters Comparison: Illinois No. 2, 3, and 5 Seam Coals, Gallatin County, Illinois and West Kentucky No. 11 Seam Coal, Union County, Kentucky (Dry Basis, except HGI)

	Illinois No. 2 Raw Coal	Illinois No. 3 Raw Coal	Illinois No. 5 Raw Coal	West Kentucky No.11 Raw Coal
ULTIMATE ANALYSIS				
Carbon (Wt %)	69.67	64.75	67.65	49.67
Hydrogen (Wt %)	4.48	4.61	4.71	3.77
Nitrogen (Wt %)	1.31	1.17	1.17	1.00
Oxygen (Wt %)	4.82	4.50	4.90	6.36
CHLORINE (Wt %)	0.31	0.36	0.28	0.08
HARDGROVE GRINDABILITY INDEX (HGI)	62	56	61	52
ASH FUSIBILITY (°F) (Reducing/Oxidizing)				
Initial Deformation	1960/2515	2015/2435	1985/2285	2120/2340
Softening	2000/2550	2030/2480	2040/2340	2175/2395
Hemispherical	2130/2570	2100/2515	2120/2400	2320/2435
Fluid	2300/2580	2240/2555	2200/2435	2420/2495
CALCULATED INDICES				
Silica Percentage	53	60	52	75
Base-to-Acid Ratio	0.67	0.48	0.75	0.28
Slagging Index (Classification)	3.32 (Severe)	2.06 (High)	3.55 (Severe)	1.07 (Medium)
Fouling Index (Classification)	0.11 (Low)	0.15 (Low)	0.43 (Medium)	0.21 (Medium)

Slagging Index Classification	
Low	< 0.6
Medium	0.6 to 2.0
High	2.0 to 2.6
Severe	> 2.6

Fouling Index Classification	
Low	< 0.2
Medium	0.2 to 0.5
High	0.5 to 1.0
Severe	> 1.0

4.1.2.2 Coal Cleanability and Impurities Liberation Assessments. Laboratory washability studies and liberation assessments were performed on the Illinois and Kentucky coals to evaluate the potential for maximizing energy recovery while removing maximum amounts of mineral matter via crushing, grinding, and cleaning.

Based on the results of these studies, there is some potential for improving the liberation of mineral matter in each of the four coals. Crushing Illinois coals to a 28 mesh topsize followed by cleaning can potentially produce clean coals having about 8 to 10 percent ash. Crushing and cleaning West Kentucky No. 11 Seam coal will yield clean coals having less than 10 percent ash only when this coal is crushed to nominal minus 100 mesh or finer. In all cases, though, liberation and removal of sulfur-bearing minerals during coal cleaning is probably effected best when the raw coals are crushed to minus 100 mesh. However, crushing to these sizes followed by cleaning could prove to be uneconomical.

4.1.2.3 Flowsheet Tests. To evaluate the practical cleanability of Illinois Basin coals that are crushed to improve mineral matter liberation and to provide data to the CQE coal database on four cleaned Illinois Basin coals, CQ Inc. engineers conducted four commercial-scale cleaning tests at the CQDC: two tests on an equal blend of the three Illinois coals and two tests on the Kentucky coal.

The Illinois coal blend was cleaned to two quality levels using a heavy-media cyclone and a 2-stage water-only cyclone/spiral flowsheet. The Kentucky coal cleaning tests were conducted using the standard CQDC heavy-media cyclone/water-only cyclone/froth flotation flowsheet (Figure 4-2) in order to produce a high yield of clean coal with quality levels that meet or exceed commercial specifications.

In the two flowsheet tests with the Illinois coal blend, the heavy-media cyclone was operated at a circulating specific gravity of 1.40 and 1.60, respectively. Table 4-6 summarizes the flowsheet performances of the coal blend and Table 4-7 gives the laboratory combustion characteristics of the raw and clean coals from these tests.

Though the ash and sulfur content of the cleaned coals from tests 1 and 2 are similar to those reported by the Jader Fuel commercial operation, clean coal yield from these flowsheet tests is slightly lower than the operating plant's 86 percent yield, probably because the amount of the Illinois No. 2 coal in the commercial plant comprises more than one-third of the blend.

In both tests, cleaning reduced the ash loading and SO_2 emissions potential of the blend by about 50 percent. Comparison of the laboratory combustion characteristics of the raw and clean Illinois coal blend in Table 4-7 shows that cleaning also reduces the slagging potential of the Illinois coal blend from severe to medium, while also decreasing its ash fusibility.

Table 4-6
Flowsheet Performance Comparison: Illinois No. 2, 3, and 5 Coal Blend (Dry Basis)

	Raw Coal	Test 1 HMC/WOC	Test 2 HMC/WOC	Field Test Baseline Coal
COAL SIZE	¾-inch X 0	¾-inch X 0	¾-inch X 0	ND
ANALYSES				
Ash (Wt %)	18.24	8.23	8.96	8.83
Volatile Matter (Wt %)	33.28	37.49	36.56	36.33
Total Sulfur (Wt %)	4.97	2.63	3.17	2.71
Pyritic Sulfur (Wt %)	3.46	0.97	1.18	0.71
Pyritic Sulfur/Total Sulfur (%)	69.6	36.9	37.2	26.2
Higher Heating Value (Btu/lb)	12,080	13,855	13,696	13,426
Ash Loading (lbs/MBtu)	15.1	5.94	6.54	6.58
SO_2 Emission Potential (lbs/MBtu)	8.23	3.80	4.63	4.04
PERFORMANCE				
Yield (Wt %)	NA	71	80	ND
Energy Recovery (%)	NA	81	91	ND
Ash Reduction (Heat Unit Basis, %)	NA	60	57	ND
SO_2 Reduction (Heat Unit Basis, %)	NA	59	52	ND

HMC = Heavy-media Cyclone WOC = Water-only Cyclone/Spiral Concentrator
NA = Not Applicable ND = Not Determined

Two tests were also conducted on the West Kentucky No. 11 Seam Coal: one test on raw coal crushed to a minus 3/4-inch top-size and one test on coal crushed to nominal minus 3/8-inch top-size. In the first test, the circulating specific gravity of the heavy-media cyclone circuit was set at 1.40, while the water-only cyclone and flotation circuits were operated at levels set to ensure high coal yields. In the second flowsheet test, a circulating specific gravity of 1.36 was used to clean crushed coal to determine if a clean coal containing less than 2.8 percent total sulfur may be produced without sacrificing clean coal yield. The flowsheet performances and the laboratory combustion characteristics of raw and clean coals from the two tests are summarized in Tables 4-8 and 4-9, respectively.

These test results show that crushing the raw coal to 3/8-inch top-size prior to cleaning with a heavy-media-based flowsheet can decrease the ash content of the coal while maximizing clean coal yield. As shown in Table 4-8, clean coal yield from Test

Table 4-7
Combustion Parameters Comparison: Illinois No. 2, 3, and 5 Coal Blend (Dry Basis, except HGI)

	Raw Coal	Test 1 HMC/WOC	Test 2 HMC/WOC	Field Test Baseline Coal
ULTIMATE ANALYSIS				
Carbon (Wt %)	65.93	75.01	74.92	74.46
Hydrogen (Wt %)	4.53	5.08	5.22	5.02
Nitrogen (Wt %)	1.22	1.45	1.40	1.50
Oxygen (Wt %)	5.13	7.60	6.33	7.17
CHLORINE (Wt %)	0.28	0.27	0.26	0.31
HARDGROVE GRINDABILITY INDEX (HGI)	58	60	60	62
ASH FUSIBILITY (°F) (Reducing/Oxidizing)				
Initial Deformation	1970/2383	2000/2480	1960/2490	1988/2405
Softening	2018/2448	2070/2525	2000/2530	2055/2466
Hemispherical	2140/2513	2200/2560	2085/2550	2156/2503
Fluid	2233/2535	2305/2600	2230/2570	2298/2534
CALCULATED INDICES				
Silica Percentage	53	67	60	66
Base-to-Acid Ratio	0.67	0.38	0.51	0.40
Slagging Index (Classification)	3.32 Severe	1.00 Medium	1.60 Medium	1.09 Medium
Fouling Index (Classification)	0.16 Low	0.11 Low	0.10 Low	0.15 Low

HMC = Heavy-media Cyclone   WOC = Water-only Cyclone/Spiral Concentrator

Slagging Index Classification		Fouling Index Classification	
Low	< 0.6	Low	< 0.2
Medium	0.6 to 2.0	Medium	0.2 to 0.5
High	2.0 to 2.6	High	0.5 to 1.0
Severe	> 2.6	Severe	> 1.0

Table 4-8
Flowsheet Performance Comparison: West Kentucky No. 11 Seam Coal (Dry Basis)

	Raw Coal	Test 1 HMC/WOC/FF	Test 2 HMC/WOC/FF	Field Test Alternate Coal
COAL SIZE	3/4-inch X 0	3/4-inch X 0	3/8-inch X 0	ND
ANALYSES				
Ash (Wt %)	35.42	6.37	5.21	6.91
Volatile Matter (Wt %)	29.10	42.34	42.91	40.51
Total Sulfur (Wt %)	3.78	2.92	2.78	2.86
Pyritic Sulfur (Wt %)	1.99	0.90	0.77	0.71
Pyritic Sulfur/Total Sulfur (%)	52.6	30.8	27.7	24.8
Higher Heating Value (Btu/lb)	9,022	13,584	13,777	13,381
Ash Loading (lbs/MBtu)	39.26	4.69	3.78	5.16
SO_2 Emission Potential (lbs/MBtu)	8.37	4.30	4.04	3.95
PERFORMANCE				
Yield (Wt %)	NA	59	48	53-55
Energy Recovery (%)	NA	84	73	ND
Ash Reduction (Heat Unit Basis, %)	NA	88	90	ND
SO_2 Reduction (Heat Unit Basis,	NA	66	68	ND

HMC = Heavy-media Cyclone WOC = Water-only Cyclone/Spiral Concentrator FF = Froth Flotation
NA = Not Applicable ND = Not Determined

1 is about 5 percentage points higher than that of the commercial cleaning plant at similar clean coal quality levels. Furthermore, the data from Test 2 indicate that intense cleaning such as that provided by heavy-media, can produce a coal having less than 6 percent ash content and a total sulfur content less than 2.8 percent for about the same yield as the commercial plant achieves currently. Unfortunately, the additional cleaning does not appear to decrease the slagging and fouling potentials of this coal significantly.

4.1.2.4 Trace Element Reduction During Coal Cleaning. As shown in Figure 4-4, the use of coal cleaning to remove mineral matter also reduces the concentration of a variety of trace elements found in these Illinois Basin coals. In addition, the data indicate that the concentration levels of trace elements in these raw coals can vary widely even when the coals are located very near one another geographically.

Table 4-9
Combustion Parameters Comparison: West Kentucky No. 11 Seam Coal (Dry Basis, except HGI)

	Raw Coal	Test 1 HMC/WOC/FF	Test 2 HMC/WOC/FF	Field Test Alternate Coal
ULTIMATE ANALYSIS				
Carbon (Wt %)	49.67	74.67	75.36	74.36
Hydrogen (Wt %)	3.77	5.27	5.54	5.07
Nitrogen (Wt %)	1.00	1.46	1.38	1.38
Oxygen (Wt %)	6.36	9.32	9.74	9.19
CHLORINE (Wt %)	0.08	0.16	0.40	0.23
HARDGROVE GRINDABILITY INDEX (HGI)	52	49	47	53
ASH FUSIBILITY (°F) (Reducing/Oxidizing)				
Initial Deformation	2120/2340	1945/2415	1960/2420	1979/2373
Softening	2175/2395	2040/2470	2005/2480	2030/2421
Hemispherical	2320/2435	2200/2505	2140/2525	2131/2465
Fluid	2420/2495	2300/2570	2300/2560	2300/2509
CALCULATED INDICES				
Silica Percentage	0.75	0.61	0.62	0.63
Base-to-Acid Ratio	0.28	0.48	0.46	0.45
Slagging Index (Classification)	1.07 (Medium)	1.40 (Medium)	1.27 (Medium)	1.29 (Medium)
Fouling Index (Classification)	0.21 (Medium)	0.42 (Medium)	0.49 (Medium)	0.35 (Medium)

HMC = Heavy-media Cyclone   WOC = Water-only Cyclone/Spiral Concentrator   FF = Froth Flotation

Slagging Index Classification		Fouling Index Classification	
Low	< 0.6	Low	< 0.2
Medium	0.6 to 2.0	Medium	0.2 to 0.5
High	2.0 to 2.6	High	0.5 to 1.0
Severe	> 2.6	Severe	> 1.0

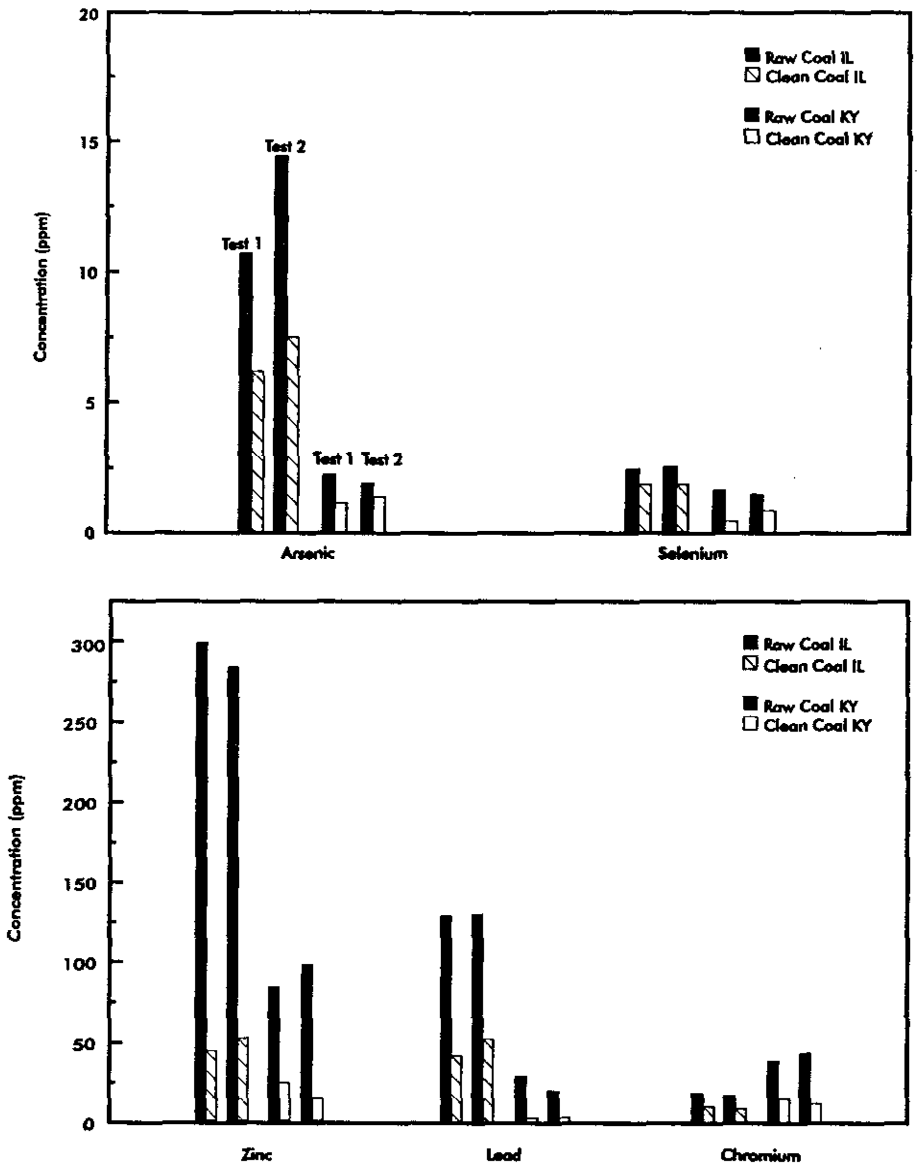


Figure 4-4
Trace Element Removal From Coal via Cleaning: Illinois No. 2, 3, and 5 Coal Blend and West Kentucky No. 11 Seam Coal (Dry Basis)

Table 4-10
Montana Raw Coal Quality Summary (SO_3-free Basis Analyses)

	Absaloka Mine Rosebud-M[c]Kay Seam Big Horn County		Rosebud Mine Rosebud Seam Rosebud County	
PROXIMATE ANALYSIS	As-Received	Dry Basis	As-Received	Dry Basis
Total Moisture (Wt %)	25.76		22.73	
Fixed Carbon (Wt %)	36.93	49.74	35.49	45.92
Volatile Matter (Wt %)	29.39	39.59	34.69	44.90
Ash (Wt %)	7.92	10.67	7.09	9.18
HIGHER HEATING VALUE (Btu/lb)	8,509	11,462	8,940	11,570
ULTIMATE ANALYSIS				
Carbon (Wt %)	55.64	74.95	51.45	66.59
Hydrogen (Wt %)	1.10	1.48	3.85	4.98
Nitrogen (Wt %)	0.64	0.86	0.77	0.99
Oxygen (Wt %)	8.36	11.25	13.49	17.46
Total Sulfur (Wt %)	0.58	0.78	0.62	0.80
Pyritic Sulfur (Wt %)	0.17	0.22	0.19	0.25
Organic Sulfur (Wt %)	0.40	0.54	0.42	0.54
SO_2 EMISSION POTENTIAL (lbs/MBtu)	1.36		1.38	
CHLORINE (Wt %)	0.03	0.04	0.04	0.05
HARDGROVE GRINDABILITY INDEX				
ASH FUSIBILITY (°F) (Reducing/Oxidizing)				
Initial Deformation		2180/2215		2150/2225
Softening		2210/2245		2190/2290
Hemispherical		2245/2305		2300/2320
Fluid		2300/2410		2360/2405
SLAGGING INDEX (Classification)		2205 (High)		2184 (High)
FOULING INDEX (Classification)		1.2 (Low)		0.2 (Low)

Slagging Index Classification

Low	> 2450
Medium	2250 to 2450
High	2100 to 2250
Severe	< 2100

Fouling Index Classification

Low to Medium	< 3
High	3 to 6
Severe	> 6

Table 4-11
Wyoming Raw Coal Quality Summary (SO_3-free Basis Analyses)

	Belle Ayr Mine Wyodak Seam Campbell County		**Rochelle Mine** Wyodak Seam Campbell County		**Antelope Mine** Wyodak-Anderson Converse County	
PROXIMATE ANALYSIS	As-Received	Dry Basis	As-Received	Dry Basis	As-Received	Dry Basis
Total Moisture (Wt %)	29.20		27.15		26.01	
Fixed Carbon (Wt %)	34.41	48.60	35.12	48.20	36.92	49.90
Volatile Matter (Wt %)	32.38	45.74	33.23	45.62	31.66	42.79
Ash (Wt %)	4.01	5.66	4.50	6.18	5.41	7.31
HIGHER HEATING VALUE	8,529	12,045	8,801	12,080	8,733	11,803
ULTIMATE ANALYSIS						
Carbon (Wt %)	48.56	68.58	51.11	70.15	50.49	68.23
Hydrogen (Wt %)	3.52	4.98	3.46	4.75	3.37	4.55
Nitrogen (Wt %)	0.67	0.95	0.66	0.91	0.79	1.07
Oxygen (Wt %)	13.70	19.36	12.90	17.72	13.65	18.44
Total Sulfur (Wt %)	0.34	0.47	0.22	0.30	0.28	0.38
Pyritic Sulfur (Wt %)	0.06	0.09	0.01	0.01	0.07	0.09
Organic Sulfur (Wt %)	0.26	0.37	0.20	0.28	0.21	0.29
SO_2 EMISSION POTENTIAL	0.78		0.50		0.64	
CHLORINE (Wt %)	0.08	0.11	0.05	0.07	0.04	0.06
HARDGROVE GRINDABILITY	63		53		47	
ASH FUSIBILITY (°F) (Reducing/Oxidizing)						
Initial Deformation		2030/2160		2125/216		2085/2135
Softening		2080/2205		2130/217		2120/2170
Hemispherical		2120/2315		2145/220		2145/2200
Fluid		2160/2410		2165/224		2200/2245
SLAGGING INDEX (Classification)		2087 (Severe)		2140 (High)		2108 (High)
FOULING INDEX (Classification)		0.9 (Low)		1.2 (Low)		2.0 (Low)

Slagging Index Classification	
Low	> 2450
Medium	2250 to 2450
High	2100 to 2250
Severe	< 2100

Fouling Index Classification	
Low to Medium	< 3
High	3 to 6
Severe	> 6

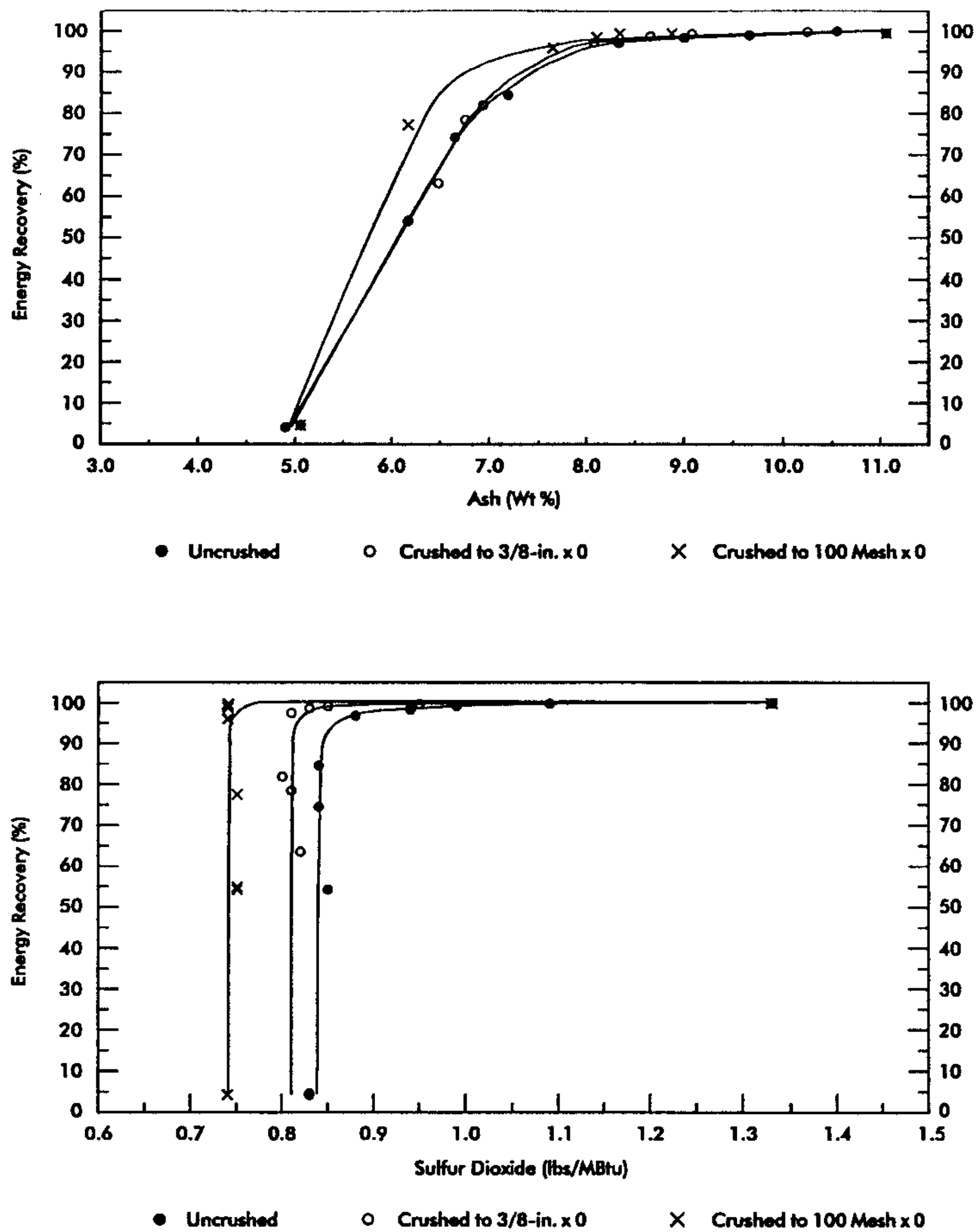


Figure 4-6
The Potential for Ash and Sulfur Reduction from Uncrushed and Crushed Absaloka Mine Coal

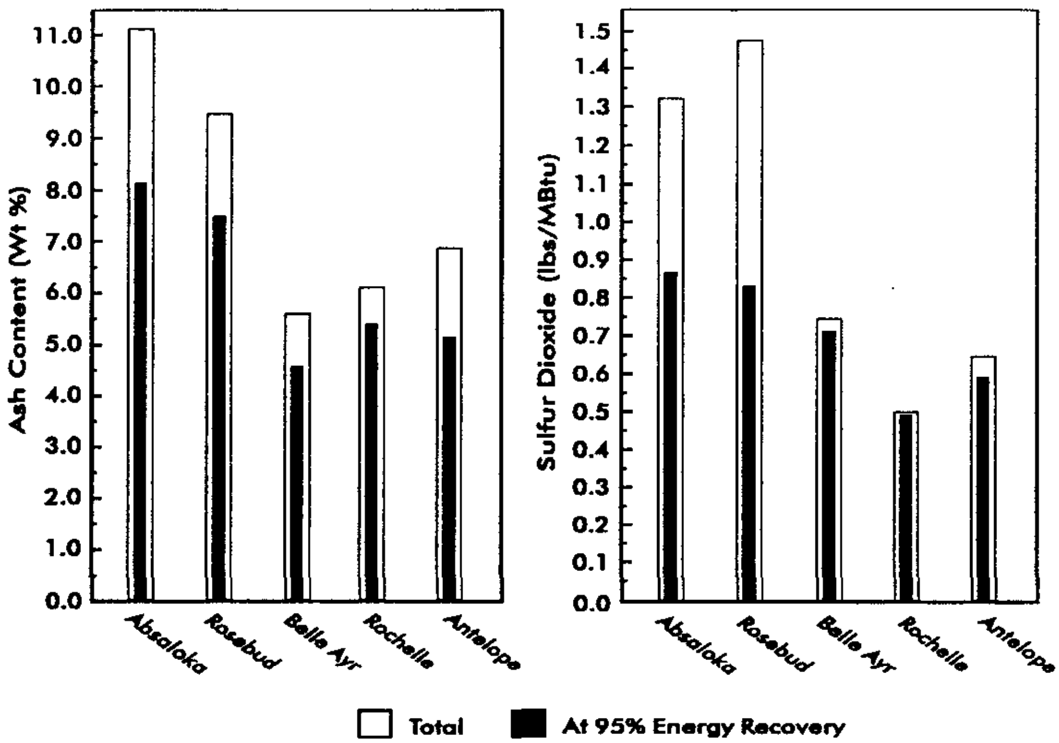


Figure 4-7
Potential Ash and Sulfur Dioxide Reduction During Cleaning of Uncrushed Powder River Basin Coals

levels by an additional 10 to 15 percent, on average, while still yielding 95 percent energy recovery. Conversely, cleaning the Wyodak coals from the interior parts of the Basin (Belle Ayr and Rochelle) after additional crushing or grinding will probably not improve greatly the reduction of ash nor provide notably lower sulfur dioxide emissions.

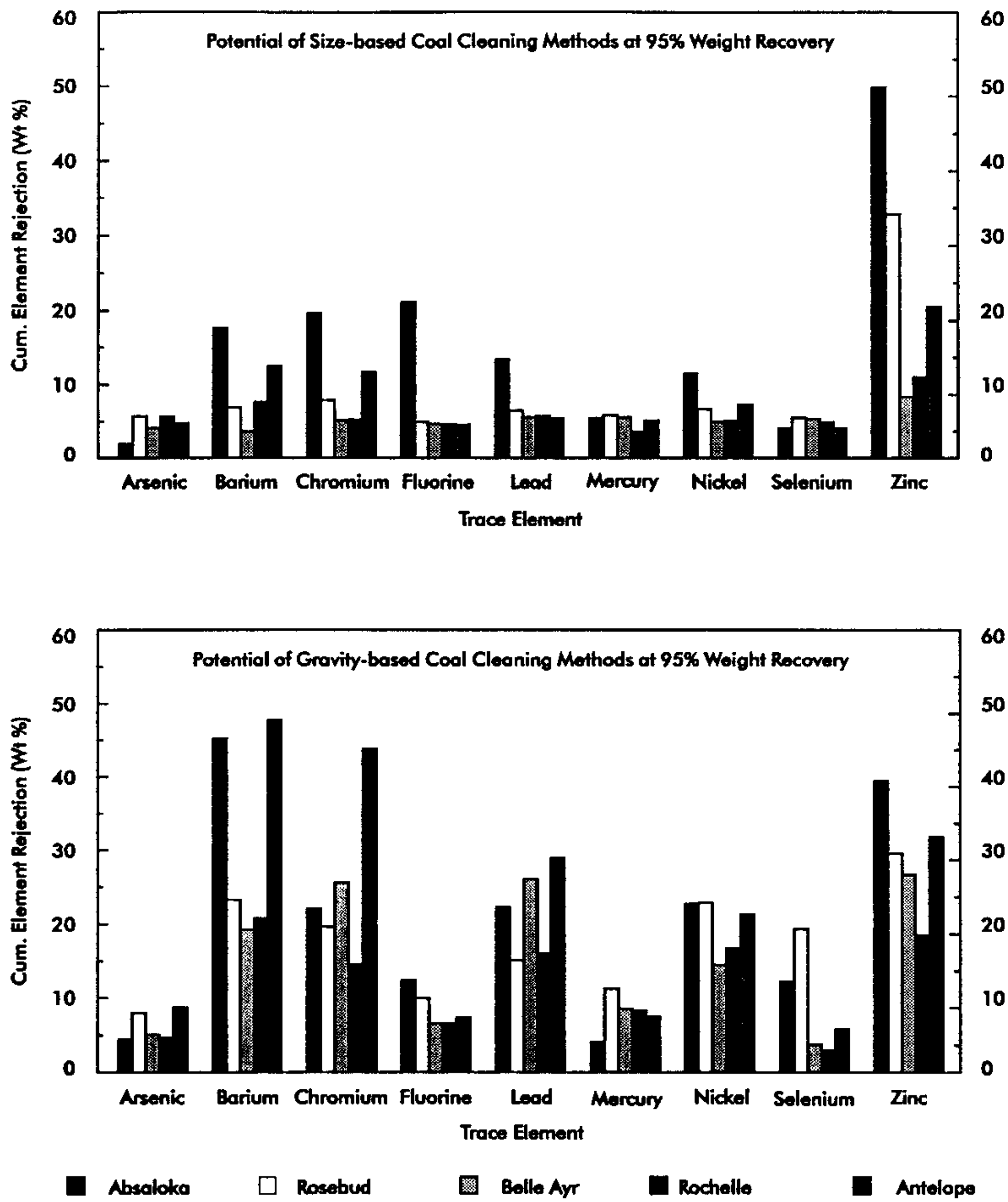
4.1.3.4 Evaluation of the Potential for Removing Trace Elements Using Physical Coal Cleaning. As shown in Table 4-12, the amounts of trace elements in the five Powder River Basin coals vary widely. For example, the coal samples from Montana generally contained more arsenic, lead, manganese, nickel, and zinc than the coals from Wyoming. Wyoming coal samples contained higher amounts of chlorine, fluorine, and mercury. Also, the Wyodak-Anderson Seam coal contained higher levels of chromium, lead, nickel, and zinc than did its two Wyoming counterparts. In all of the samples analyzed, the levels of antimony, cadmium, and silver were lower than that which can be detected and measured accurately.

Table 4-12
Raw Coal Trace Element Summary
(SO_3-free, Ash-basis Dry Basis Analyses in ppm)

Trace Element	Absaloka	Rosebud	Belle Ayr	Rochelle	Antelope
Arsenic	4.0	3.6	2.5	1.5	2.3
Chlorine	400	500	1100	700	600
Chromium	3.9	3.5	2.7	2.7	4.6
Fluorine	34.1	37.7	57.2	48.5	45.5
Lead	4.9	5.0	2.4	1.8	3.2
Lithium	24.1	8.9	2.1	12.6	4.8
Manganese	78.1	110.0	48.1	10.0	15.3
Mercury	0.19	0.16	0.29	0.23	0.24
Nickel	6.3	5.3	3.5	2.5	4.6
Selenium	1.8	1.4	1.2	1.7	1.8
Zinc	16.7	9.0	8.2	5.7	10.6

Values given are averages of all available head, size composite, and gravity composite analyses.

Potentially, the use of coal cleaning may reject anywhere from zero to 50 percent of the amount of each of nine elements of concern. As shown in Figure 4-8, sizing the two Montana coals and Antelope Mine coal may effectively reject significant amounts of barium, chromium, fluorine, lead, nickel, and zinc without sacrificing more than five percent energy recovery. Gravity-based coal cleaning techniques can potentially decrease the barium, chromium, lead, nickel, and zinc levels of all five coals. Crushing any of the five coals to minus 100 mesh topsize to increase the liberation of trace element-bearing minerals does not improve the rejection of elements during coal cleaning significantly.



$$\% \ \textit{Element Rejection} = 100 - \left[100 \times \frac{(\% \ \textit{Trace Element in Clean Coal} \times \textit{Clean Coal Weight})}{(\% \ \textit{Trace Element in Raw Coal} \times \textit{Raw Coal Weight})}\right]$$

Figure 4-8
Potential Rejection of Trace Elements During Cleaning of Uncrushed Powder River Basin Coal

4.1.4 APC Gaston Station Coals

In late 1991 and early 1992, coal cleanability characterizations were completed on 400-ton and 100-ton samples of Pratt and Utley seam coals from Pittsburg and Midway Coal Mining Company's North River No. 1 and Meg No. 5 mines, respectively, which are located near Berry, Alabama.

The analyses shown in Table 4-13 indicate that raw Pratt and Utley seam coals are high volatile A/B bituminous in rank, containing moderate to high amounts of ash-forming and sulfur-bearing mineral matter. Ash fusion and chemical composition data indicate that Pratt Seam coal has a low slagging potential, while Utley Seam coal has a medium to high slagging potential. The Utley Seam coal contains about 2.5-times more ferric oxide than the Pratt Seam coal, but both coals have relatively low fouling potential. Additional analyses also show that, as mined, both coals contain a moderate amount of high-ash, low-sulfur minus 325 mesh material.

4.1.4.1 Coal Cleanability and Impurities Liberation Assessments. The quality of both the Pratt and Utley seam coals can be improved using coal cleaning techniques. For example, Figure 4-9 shows that crushing and cleaning operations can reduce the ash content of Pratt Seam coal by over 65 percent while achieving 90 to 95 percent energy recovery. However, intense cleaning techniques, including crushing to a topsize of at least minus 100 mesh, will likely be required to produce clean coal having SO_2 emissions levels of 2.5 lbs/MBtu or less. The cleaning and liberation potentials for Utley Seam coal are similar to those of the Pratt Seam coal.

4.1.4.2 Flowsheet Testing. To evaluate the effectiveness of coal cleaning on Pratt and Utley seam coals, project engineers completed four flowsheet tests: one with the CQDC standard heavy-media cyclone/water-only cyclone/froth flotation flowsheet, two with a concentrating table flowsheet, and one with a concentrating table/spiral concentrator flowsheet (Figure 4-10). The standard flowsheet was used to represent an intense cleaning application, while the concentrating table flowsheets were used to represent low-cost cleaning options either with or without a specific circuit for removing sulfur-bearing pyrite. A summary of results for all flowsheet tests is given in Tables 4-14 and 4-15.

Raw coal feed for all tests was crushed to minus 3/8-inch topsize. The circulating specific gravity for the heavy-media cyclone circuit in Flowsheet 1 was 1.60. No attempt was made to clean or recover nominal -100 mesh coal in either Flowsheet 2 or 3.

As shown in Table 4-14, clean coal yield from these four flowsheet tests ranged from 52 to 72 percent. Only cleaning in Flowsheet 1 produced an energy recovery exceeding 86 percent. A comparison of the responses of Pratt Seam (Test 2) and

Table 4-13
Raw Coal Quality Summary for Pratt and Utley Seam Coals (Dry basis analyses except where noted)

	Pratt Seam Fayette County, AL	Utley Seam Tuscaloosa County, AL
Total Moisture (As-received) (Wt %)	6.64	6.71
Fixed Carbon (Wt %)	42.63	48.35
Volatile Matter (Wt %)	31.51	36.38
Ash (Wt %)	25.86	15.27
Higher Heating Value (Btu/lb)	10,777	12,594
Total Sulfur (Wt %)	2.13	3.81
Pyritic Sulfur (Wt %)	1.10	2.16
Organic Sulfur (Wt %)	1.01	1.42
SO_2 Emission Potential (lbs/MBtu)	3.95	6.04
Carbon (Wt %)	59.55	68.19
Hydrogen (Wt %)	4.89	4.86
Nitrogen (Wt %)	1.36	1.27
Oxygen (Wt %)	6.71	6.60
Chlorine (Wt %)	0.08	0.05
Hardgrove Grindability Index (HGI)	62	66
Ash Fusibility (Reducing/Oxidizing)		
Initial Deformation (°F)	2450/2580	1995/2440
Softening (°F)	2505/2610	2080/2490
Hemispherical (°F)	2550/2665	2200/2515
Fluid (°F)	2605/2710	2315/2540
Slagging Index (Classification)	0.54 (Low)	1.88 (Medium)
Fouling Index (Classification)	0.13 (Low)	0.12 (Low)

Slagging Index Classification	
Low	< 0.6
Medium	0.6 to 2.0
High	2.0 to 2.6
Severe	> 2.6

Fouling Index Classification	
Low	< 0.2
Medium	0.2 to 0.5
High	0.5 to 1.0
Severe	> 1.0

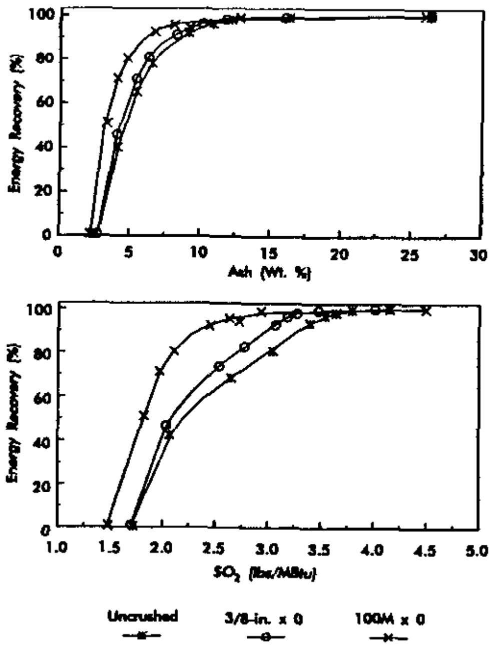


Figure 4-9
Potential Ash and SO_2 Reduction of Uncrushed and Crushed Pratt Seam Coal

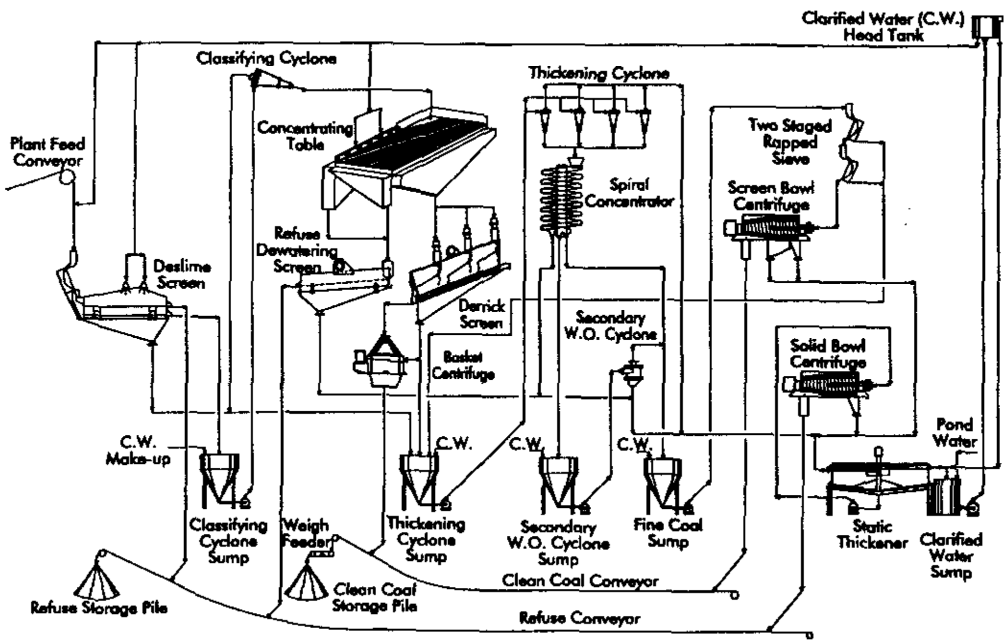


Figure 4-10
CQDC Concentrating Table Flowsheet with Spiral Concentrator Option

Table 4-14
Flowsheet Performance Comparison: Pratt and Utley Seam Coals, Alabama

	Test 1 90% Pratt/10% Utley Blend HMC/WOC/FF		Test 3 Utley Seam CONC. TABLE	
ANALYSES	RAW COAL	CLEAN COAL	RAW COAL	CLEAN COAL
Ash (Wt %)	24.3	7.6	15.7	9.6
Total Sulfur (Wt %)	2.48	2.29	3.65	2.80
Pyritic Sulfur (Wt %)	1.43	1.27	2.46	1.02
Pyritic Sulfur/Total Sulfur (%)	57.6	55.4	67.4	36.4
Higher Heating Value (Btu/lb)	11,121	13,872	12,578	13,570
Ash Loading (lbs/MBtu)	21.8	5.5	12.5	7.0
SO_2 Emission Potential (lbs/MBtu)	4.46	3.30	5.80	4.13
PERFORMANCE				
Yield (Wt %)	NA	72	NA	58
Energy Recovery (%)	NA	89	NA	63
Ash Reduction (Heat Unit Basis, %)	NA	75	NA	43
SO_2 Reduction (Heat Unit Basis, %)	NA	26	NA	34

	Test 2 Pratt Seam CONC. TABLE		Test 4 Pratt Seam TABLE/SPIRAL	
ANALYSES	RAW COAL	CLEAN COAL	RAW COAL	CLEAN COAL
Ash (Wt %)	28.0	11.9	27.3	8.7
Total Sulfur (Wt %)	2.21	2.13	2.33	2.23
Pyritic Sulfur (Wt %)	1.24	1.05	1.49	1.35
Pyritic Sulfur/Total Sulfur (%)	56.1	49.3	63.9	60.5
Higher Heating Value (Btu/lb)	10,582	13,050	10,686	13,717
Ash Loading (lbs/MBtu)	26.5	9.1	25.5	6.3
SO_2 Emission Potential (lbs/MBtu)	4.18	3.26	4.36	3.25
PERFORMANCE				
Yield (Wt %)	NA	52	NA	58
Energy Recovery (%)	NA	64	NA	73
Ash Reduction (Heat Unit Basis, %)	NA	65	NA	75
SO_2 Reduction (Heat Unit Basis, %)	NA	37	NA	42

HMC = Heavy-media Cyclone
WOC = 2-Stage Water-only Cyclone
FF = Froth Flotation
Conc. Table = Concentrating Table
Spiral = Spiral Concentrator
NA = Not Applicable

Table 4-15
Clean Coal Combustion Parameters Comparison: Pratt and Utley Seam Coals, Alabama (Dry Basis, except HGI)

	Test 1 90% Pratt/10% Utley Blend HMC/WOC/FF	Test 2 Pratt Seam CONC. TABLE	Test 3 Utley Seam CONC. TABLE	Test 4 Pratt Seam TABLE/SPIRAL
ULTIMATE ANALYSIS				
Carbon (Wt %)	76.1	72.0	73.7	75.0
Hydrogen (Wt %)	5.3	5.1	5.3	5.3
Nitrogen (Wt %)	1.7	1.4	1.5	1.7
Oxygen (Wt %)	6.9	7.5	7.1	7.1
CHLORINE (Wt %)	0.17	0.04	0.03	0.07
HARDGROVE GRINDABILITY INDEX (HGI)	49	50	53	49
ASH FUSIBILITY (°F) (Reducing/Oxidizing)				
Initial Deformation	2080/2495	2160/2460	1995/2475	2175/2510
Softening	2175/2520	2225/2500	2100/2505	2250/2540
Hemispherical	2270/2535	2320/2535	2225/2525	2330/2575
Fluid	2350/2550	2410/2575	2365/2555	2400/2590
CALCULATED INDICES				
Silica Percentage	52	62	53	60
Base-to-Acid Ratio	0.53	0.39	0.58	0.41
Slagging Index (Classification)	1.2 (Medium)	0.8 (Medium)	1.6 (Medium)	0.9 (Medium)
Fouling Index (Classification)	0.28 (Medium)	0.16 (Low-Medium)	0.20 (Low-Medium)	0.16 (Low-Medium)

HMC = Heavy-media Cyclone
Conc. Table = Concentrating Table
WOC = 2-Stage Water-only Cyclone
Spiral = Spiral Concentrator
FF = Froth Flotation

Slagging Index Classification	
Low	< 0.6
Medium	0.6 to 2.0
High	2.0 to 2.6
Severe	> 2.6

Fouling Index Classification	
Low	< 0.2
Medium	0.2 to 0.5
High	0.5 to 1.0
Severe	> 1.0

Utley Seam (Test 3) coals to cleaning by the same flowsheet shows that ash reduction was markedly higher for Pratt Seam coal than for Utley Seam coal, but that the reductions of sulfur dioxide precursors were similar. Cleaning results from Test 4 show that the addition of a spiral concentrator circuit to the table flowsheet did not improve the removal of pyrite from Pratt Seam coal significantly, but the use of this intermediate-size coal cleaning circuit did help to reduce the ash content of the clean coal by another three percentage points.

As indicated by the data in Table 4-15, concentrating table-based flowsheets reduced the calcareous and siliceous mineral matter content of both the Pratt and Utley seam coals adequately. However, these flowsheets did not reduce the alumina and aluminosilicate contents as well as did Flowsheet 1.

Unfortunately, in the case of the Pratt Seam coal, the use of coal cleaning appears to have exacerbated some of its combustion problems. Coal cleaning decreased the ash fusion temperatures of the Pratt Seam coal and increased its slagging and fouling potentials. This is probably the result of the inability of these flowsheets to remove iron oxide- and alkali metal-bearing minerals as readily as other ash-forming mineral matter. In addition, cleaning in Flowsheet 1 increased the chlorine concentration of the Pratt/Utley blend over two-fold. For the most part, the ash composition and fusibility of Utley Seam coal was unaffected by cleaning, even though substantial amounts of mineral matter were removed.

4.1.4.3 Trace Element Reduction During Coal Cleaning. In addition to removing ash-forming and sulfur-bearing minerals, cleaning reduced the concentrations of many trace elements found in the Pratt and Utley seam coals. Figure 4-11 shows that, irrespective of flowsheet design, cleaning reduced the trace element content of Pratt Seam coal more than did cleaning of Utley Seam coal. Furthermore, cleaning decreased the concentrations of elements that are associated with ash-forming minerals (barium, chromium, fluorine, lead, nickel, and zinc) more than those of the other elements. These results also indicate that equipment selection, configuration (flowsheet design), and their method of operation affect the relative removal of trace elements from these coals.

4.2 Pilot Scale Combustion Tests

Pilot-scale combustion tests were conducted to support the coal cleanability characterization and field testing efforts. ABB/CE was responsible for all pilot-scale combustion tests, with the exception of the cyclone boiler simulations, which were the responsibility of B&W. Bench-scale tests were performed by ABB/CE, B&W, and the UNDEERC under the general direction of ABB/CE.

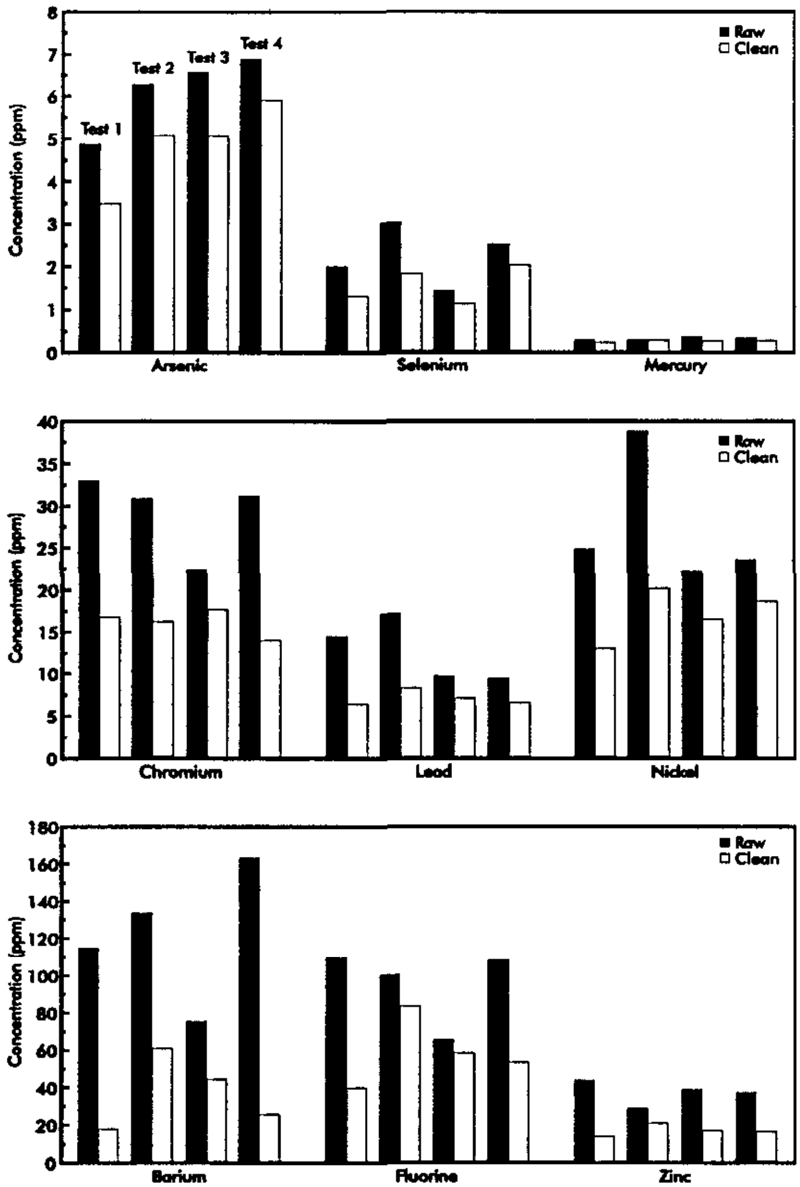


Figure 4-11
Trace Element Concentrations in Pratt and Utley Seam Coals: Raw and Clean Coal Analyses by Flowsheet Test

Four pilot-scale combustion test series were completed. This task provided detailed characterization of fuel properties of the test coals and in depth evaluation of their performance characteristics under controlled pilot-scale combustion testing. Results from this task provided much of the fundamental information required to develop the improved algorithms for CQE. The following subtasks comprised the pilot-scale combustion test program:

- Bench-Scale Fuel Characterization
- Test Furnace Performance Evaluation

- Data Analysis and Reporting

All coals tested under the pilot- and bench-scale combustion test program are listed in Table 4-16. These coals--with the exception of the blend of 70 percent run-of-mine Wyoming coal and 30 percent cleaned Oklahoma coal (70 WY/30 OK Cleaned) evaluated for the Northeastern site--were collected during field testing and shipped to the pilot test sites. The Oklahoma portion (Croweburg Seam) of the 70 WY/30 OK (Cleaned) blend was cleaned at CQ Inc. and supplied to the pilot test site.

Table 4-16
Pilot- and Bench-Scale Combustion Test Program

Power Plant	Coal	Sulfur Content	Pilot Test	Bench Test
Northeastern	100 WY	Low	X	X
	100 OK	Low	X	X
	90 WY/10 OK	Low	X	X
	70 WY/30 OK	Low	X	X
	70 WY/30 OK (cleaned)	Low	X	X
Watson	Baseline (IL)	High	X	X
	Alternate (KY)	High	X	X
King	Baseline (70 WY/20 MT/10 Pet Coke)	Low	X	X
	Alternate (93 WY/7 Pet Coke)	Low	X	X
Gaston	Baseline (AL)	High	X	X
	Alternate (WV)	Low		X
Brayton Point 3	Baseline (WV)	Medium		
	Alternate (WV)	Low		X
Brayton Point 2	Baseline (WV)	Low		
	Alternate (KY)	Low		X

4.2.1 Bench-Scale Fuel Characterization

Comprehensive bench-scale tests were performed on all pulverized- and cyclone-fired test coals. These tests provided detailed fuel property data for correlation with performance characteristics established during pilot-scale and field testing. The bench-scale characterization included a battery of tests consisting of ASTM analyses, specialty tests, and advanced analytical techniques.

ASTM coal analyses were performed to help set pilot-scale operating conditions, including:

- Proximate analysis
- Ultimate analysis
- Gross heating value
- Sulfur forms
- Ash analysis for major constituents

- Ash fusion temperatures

Bench-scale testing at ABB CE also included the following measurements:

- Fuel reactivity measurements
- Specialty testing on weak acid leaching of alkalies (related to fouling)
- Quartz analysis (related to coal abrasion)

Bench-scale testing at UNDEERC involved some advanced analyses of coal and in-flame particulate deposit samples, including:

- *Computer controlled scanning electron microscopy (CCSEM)*. Used to quantify and size discrete mineral grains in coal and ash deposits. Approximately 2,000 grains are analyzed in a polished section of the deposit, and each mineral is classified according to its chemistry. The system is set up to analyze for 12 elements: Na, Mg, Al, Si, P, S, Cl, K, Ca, Fe, Ba, and Ti. This information was used in turn to elucidate the mechanisms of ash transformation and as input data to the slagging and fouling algorithms.

- *Scanning electron microscope point count (SEMPC)*. The SEM technique was most commonly used under the CQE project. SEMPC quantitatively determines the relative amount of phases present in entrained ashes and deposits, and involves microprobe analysis (chemical compositions) of a large number of random points in a polished cross section of a sample.

- *Chemical fractionation*. Determines the association of inorganic elements present in coals. It is especially useful in determining the abundance of organically-associated components (e.g., Na, Ca, and Mg) found in lignitic and subbituminous coals present as the salts of organic acid groups. These components often form small particles and low-melting-point phases during combustion; often, the mode of occurrence (as minerals or as salts of organic acid groups) is as important as the amount present.

- *X-Ray fluorescence*. Determines a bulk chemical analysis and used to verify the SEMPC results.

- *X-Ray diffraction*. Determines the mineral phases directly based on their crystal structure, and is used to verify the presence of major crystalline phases and corroborate SEMPC results.

- *Scanning electron microscopy morphology*. SEM morphologic analyses were performed on boiler ash deposits to observe the physical and chemical characterization of the bonding matrix in the deposits.

- *Malvern particle sizing*. Determines particle size distributions of coal and ash samples.

- *Loss-on-ignition (LOI)*. Determines the unburned carbon content of ash.

These analyses were primarily related to better understanding and predicting ash deposit effects. Drop-tube furnace testing was performed at both ABB/CE and UNDEERC to provide in depth combustion kinetic data, fly ash formations, and deposition data.

Bench-scale testing at B&W included:

- Yancey Geer Price (YGP) abrasion
- Erosiveness
- Inflammability temperature
- Measured slag viscosity
- Ash sintered strength
- Burning profile

B&W's erosiveness test provides predictive information about the erosive wear rate on pulverized coal (PC) preparation and transport equipment. Tests were performed on the four Northeastern coals and two Watson coals; the coal samples were shipped to B&W as as-fired pulverized coal, with the minus 200 mesh size fraction ranging from 77.3 to 84.4 percent. The test method is based on impingement of PC entrained in a gas stream on a target plate composed of low carbon steel. A PC erosiveness index, equivalent to the metal loss as measured before and after weighing of the target plate, was determined for each coal. Past B&W correlations with actual field data indicate that a coal having an erosiveness index value greater than 36 is characterized as a highly erosive coal. Very low erosiveness was indicated for these test coals (Table 4-17), except for the Northeastern 70 WY/30 OK blend which--with an index value of 27.45--is considered to be an erosive coal, although not to a great extent.

Table 4-17
Erosiveness Values of Northeastern and Watson Test Coals

Test Coal	Erosion Index (mg/15 lb. coal)
Northeastern 100 WY	9.60
Northeastern 90 WY/10 OK	14.55
Northeastern 70 WY/30 OK	27.45
Northeastern 70 WY/30 OK_{CL}	11.70
Watson Jader	11.85
Watson Island Creek	10.20

4.2.2 Test Furnace Performance Evaluation

During this subtask, ABB CE's Fireside Performance Test Facility (FPTF) and B&W's Small Boiler Simulator (SBS) were used to evaluate the effects of coal properties on pulverization, ash deposition, combustion, erosion, and emissions. The primary purpose of this work was to provide data that can be used to predict full-scale boiler combustion performance from pilot-scale tests, while providing detailed quantitative performance data for CQE algorithm development.

The FPTF pilot combustion test matrix was expanded to address the effects of excess air on fuel performance. Additional test runs were conducted at both high and low excess air levels to elucidate the impacts on ash deposition. Testing under controlled conditions in the FPTF allows separation of the combined effects on ash deposition due to ash chemistry differences associated with the different atmosphere and differences in thermal environment due to the dilution effects associated with high or low air input.

4.2.2.1 PSO Northeastern Unit 4 - Wyoming and Oklahoma Coals. The FPTF was used to evaluate the effects of coal properties on pulverization, ash deposition, combustion, erosion, and emissions. Table 4-18 summarizes the firing conditions matrix for the four Northeastern test coals.

Table 4-18
FPTF Firing Conditions Test Matrix for Northeastern Coals

Test Coal	Duration (hrs)	Firing Rate (MBtu/hr)	Avg Operating Temperature (°F)	Excess Air (%)
100% WY	12	3.6	2900-2925	20
	12	3.4	2850-2875	20
	12	3.2	2800-2825	20
	12	3.3	2825-2850	12.5
	12	3.3	2825-2850	30
	12	3.3	2825-2850	20
90 WY/10 OK	12	3.3	2825-2850	20
	12	3.7	2925-2950	20
	9	4.0	3000-3025	20
	12	3.8	2950-2975	12.5
	12	3.8	2950-2975	30
	12	3.7	2925-2950	20
70 WY/30 OK	12	3.7	2925-2950	20
	12	3.3	2825-2850	20
	12	3.0	2700-2725	20
	12	3.2	2800-2825	12.5
	12	3.2	2800-2825	30
	12	3.2	2800-2825	20
70 WY/30 OK_{CL}	12	3.2	2800-2825	20
	12	3.6	2900-2925	20
	12	4.0	3000-3025	20

The 100 percent Wyoming coal formed deposits that were significantly more removable over a wide range of loads compared to the other Northeastern blends tested. The general trend shows that fouling deposit bonding strength increased with the amount of Oklahoma raw coal in the blend.

The critical thermal conditions indicated that the 70 WY/30 OK cleaned coal blend was able to be fired at the highest firing rate without limiting the heat adsorption in the lower furnace; however, the increased temperature and buildup rates resulting in the upper furnace would cause fouling deposit formations which would be non-removable with soot blowers, thus limiting boiler performance.

During FPTF testing, slag deposits were collected on sacrificial probes inserted in the lower furnace sections. If only the viscosity of these deposits is considered, the ranking of deposit severity was as follows (worst to best):

- 90 WY/10 OK
- 100 WY
- 70 WY/30 OK_{CL}
- 70 WY/30 OK

The ranking of the coals is in agreement somewhat with the comparison of heat flux for the same coals. The heat flux ranking was as follows (lowest to highest):

- 100 WY
- 90 WY/10 OK
- 70 WY/30 OK
- 70 WY/30 OK_{CL}

Viscosities affect deposit crushing strength, adhesion strength, and, consequently, the ability of the deposit to resist soot blowing action, but will not necessarily give information on expected heat flux temperatures. In reference to heat flux recovery after soot blowing, it was determined that the 100 WY and 70 WY/30 OK performed the poorest, followed by the 90 WY/10 OK and 70 WY/30 OK_{CL}.

Additional information on FPTF test results and ash deposit characterizations can be found in project technical reports and papers (see Bibliography).

4.2.2.2 MPC Watson Unit 4 - Illinois and Kentucky Coals. ABB CE's FPTF was used to evaluate the effects of coal properties on pulverization, ash deposition, combustion, erosion, and emissions. Test conditions are summarized in Table 4-19; both test coals–the baseline Illinois seam coals and the alternate Kentucky No. 11 Seam coal–were evaluated under regular and low excess air conditions.

Results show that the baseline coal had better slagging performance than the alternate coal, and that fouling performances were similar. Low excess air decreased slagging performance in both coals. The pilot-scale combustion test results showed good correlation with the Watson field test results.

SEMPC analysis was used to obtain chemical data on the waterwall panel and superheater probe deposits generated during pilot-scale FPTF combustion testing of the Watson test coals. From these analyses, it was possible to separate liquid phases from solid or crystalline phases and then derive the viscosity of the liquid phases. A deposit that has more low-viscosity liquid phases will have a tendency to become more of a troublesome slagging or fouling deposit.

Comparing the waterwall deposits from the pilot-scale firing of the Watson baseline Illinois coal and alternate Kentucky coal, it appears that the alternate coal tests at normal and high levels of excess air produced more low-viscosity liquid phase material. This confirmed results obtained from full-scale testing at the Watson Plant, which showed that the alternate coal was more of a slagging coal than the baseline coal. With respect to fouling, the viscosity distribution of silicate liquid phases in the FPTF superheater deposit was lower for the alternate coal tests, indicating that more severe fouling could occur during combustion of the alternate coal as compared to the baseline coal.

Table 4-19
FPTF Firing Conditions Test Matrix for Watson Coals

Test Coal	Duration (hrs)	Firing Rate (MBtu/hr)	Avg Operating Temperature (°F)	Excess Air (%)
Baseline	12	3.6	2896	20
Illinois No. 2,3,5	12	3.8	2949	20
	12	4.0	3013	20
	12	4.0	3013	20
	12	4.0	2983	10
	12	4.0	2989	10
	12	3.8	2978	10
	12	3.6	2912	10
Alternate	12	3.6	2905	20
Kentucky No. 11	12	3.8	2946	20
	12	3.5	2870	20
	12	3.6	2969	20
	12	3.6	2917	10
	12	3.4	2888	10
	12	3.2	2833	10
	12	3.6	2915	30

4.2.2.3 NSP King Unit 1 - Powder River Basin Coals. The King pilot-scale combustion tests were performed in a pilot-scale cyclone furnace at B&W's Alliance Research Center. Because of the small size of the cyclone, the feed coal was pulverized. The baseline coal sampled at the King Station for use in the pilot test was a blend of 70 percent Wyoming low-sulfur subbituminous coal (Wyodak-Anderson seam), 20 percent Montana low-sulfur subbituminous coal (Rosebud-McKay seam), and 10 percent high-sulfur petroleum coke. For the alternate coal test, the blend consisted of 93 percent Wyoming coal and 7 percent petroleum coke.

The King baseline and alternate pilot combustion tests were each conducted over a continuous period of approximately 30 hours. Samples of as-received coal, pulverized coal, slag, and fly ash were collected during both tests. Data were taken on superheater probe heat flux, operating conditions, and gaseous emissions. The operational conditions were continuously monitored and recorded every two hours along with the gaseous emissions data. A sacrificial furnace deposition probe was installed for each coal. After each test, the probe was removed, set in clear epoxy, and shipped to UNDEERC for analysis of the deposits.

Table 4-20 summarizes the results of the operational conditions and stack gas emissions for the baseline and alternate coal tests. Both tests were run at approximately three percent excess oxygen at the stack. Loads for the baseline and alternate coal tests were 6 MBtu/hr and 5 MBtu/hr, respectively. The operational conditions were continuously monitored and recorded every two hours along with the gaseous emissions data. Because of some problems with the coal feed system, a limited amount of data was not recorded because it did not represent optimum conditions. A final report for the SBS testing is referenced in the bibliography.

Table 4-26
Test Coal Analyses--MPC Watson Unit 4

	Baseline Illinois (Jader)	Alternate Kentucky (Island Creek)
PROXIMATE ANALYSIS (Wt %, As-received)		
Total Moisture	6.49	11.66
Ash	8.26	6.10
Volatile Matter	33.97	35.79
Fixed Carbon	51.28	46.45
Higher Heating Value (Btu/lb)	12,555	11,821
Total Sulfur (Wt %)	2.53	2.53
SO_2 Emission Potential (lb/Mbtu)	4.03	4.28
Ash (lb/MBtu)	6.58	5.16
Hardgrove Grindability Index (HGI)	62	52
ULTIMATE ANALYSIS (Wt %, As-Received)		
Carbon	69.63	65.69
Hydrogen	4.69	4.48
Nitrogen	1.40	1.22
Sulfur	2.53	2.53
Ash	8.26	6.10
Oxygen	6.72	8.14
ASH FUSIBILITY (°F)		
(Reducing/Oxidizing)		
Initial Deformation	1988/2405	1979/2373
Softening	2055/2466	2030/2421
Hemispherical	2156/2503	2131/2465
Fluid	2298/2534	2300/2509
ASH COMPOSITION (Wt%)		
SiO_2	48.39	45.77
Al_2O_3	19.09	18.91
Fe_2O_3	21.00	21.09
CaO	3.06	4.67
MgO	1.08	0.76
Na_2O	0.36	0.79
K_2O	2.06	2.09
TiO_2	0.78	0.75
P_2O_5	0.19	0.19
SO_3	2.45	4.10

determine the effect of certain operating variables, including high and low operating O_2 levels and maximum load (255-265 MW) testing. Testing of both coals concluded with special slagging/fouling tests to investigate the effect of coal quality and plant operations on slagging, fouling, and ash carbon content. Slagging and fouling probes were inserted into the furnace to characterize ash deposition rates and properties. Test equipment and instrumentation were similar to that used at PSO Northeastern Unit 4 (Table 4-24).

Test results and conclusions from the Watson field test are summarized below:

- No significant difference in specific pulverizer power requirements.
- 30-40 percent higher primary air flow measured for the alternate coal
- Higher fineness for the alternate coal (as a result of higher primary air flow).
- 30-40 percent higher burner primary air/fuel ratios with the alternate coal.
- 5-10 percent higher coal flow on left side of the furnace with both coals.
- Delayed flame ignition for the alternate coal.
- 50-70°F higher furnace exit gas temperatures (FEGT) for the alternate coal.
- Increased furnace slag coverage for the alternate coal.
- Wetter slag consistency for the alternate coal.
- Greater superheater bridging potential for the baseline coal as a result of the plastic nature of ash at FEGT.
- Increased soot-blowing with the alternate coal.
- Lower economizer outlet temperatures with the alternate coal; cleaner super heater in unplugged regions.
- Greater slag deposition rates for the baseline coal at superheaters.
- Similar convection pass fouling rates for both coals.
- Higher low temperature corrosion potential for the alternate coal indicated by mass accumulation.
- The particulate and gas characteristics of the alternate coal were not significantly different from the baseline coal in ways that would affect ESP performance.

- The difference in ESP performance between the two test programs was almost entirely the result of ESP mechanical problems.

- Operation at or below the sulfuric acid dewpoint was occurring at locations in the ESP inlet duct. This could contribute to corrosion and possible ash deposit problems in the ESP.

4.3.4 NSP King Unit 1--Powder River Basin Coals

Northern States Power's King Unit 1 was the third of six test sites selected for utility boiler field testing under this program. It is located in Bayport, Minnesota, and consists of a B&W 580-MWg, cyclone-fired, supercritical boiler that was commissioned in 1968. The boiler nameplate rating is 3.873×10^6 lb/hr of steam flow at 1005°F superheat temperature and 3675 psi; design reheat is also 1005°F at 676 psi. The boiler is a single-furnace configuration with two cyclone elevations on the front and rear furnace walls, with each wall having six cyclone burners arranged in a three-wide-by-two high burner pattern.

Burn tests were conducted to assess the coal quality impacts on boiler performance and emissions resulting from the burning of the typical, or baseline, coal blend and an alternate coal blend. The initial baseline coal was a blend of 70 percent Wyoming subbituminous (North Antelope) coal, 20 percent Montana subbituminous (Westmoreland) coal, and 10 percent petroleum coke. The alternate coal was a blend of 93 percent Wyoming subbituminous coal and 7 percent petroleum coke. Table 4-27 summarizes the coal analytical data for these blends.

Because King 1 is base-loaded during the summer months, testing was not permitted during July and August. It was decided to split the testing of the two coals prior to and following the summer peak. Testing of the baseline coal occurred over the period May 13 through May 31, 1991, and the alternate coal was tested November 7-22, 1991.

Following a brief series of diagnostic tests, the baseline coal test burn was conducted according to the matrix developed for this site. In addition to a detailed emissions and performance characterization at full load, tests were performed at varying levels of load and excess air. Tests of specific interest to NSP were performed to examine in more detail the fouling and carbon burnout characteristics of the coal blend when operating the unit under particularly demanding operating conditions.

Baseline testing was interrupted and delayed early in the test series as a result of stack opacity problems with the original baseline test coal. It was thought that this may have been a result of a couple test coal shipments containing lower sulfur and sodium content than normal (although still within the fuel specification). Daytime peak load was reduced from 550 MW to 480 MW or less to maintain opacity within the 20-percent limits. For a period of a couple days, the baseline coal was changed to a blend of 65 WY/20 MT/15 PC to increase SO_2/SO_3 levels to the ESP and reduce opacity.

Table 4-27
Test Coal Analyses–NSP King Unit 1

	Baseline 70 WY/20 MT/10 Pet Coke	Alternate 93 WY/7 Pet Coke
PROXIMATE ANALYSIS (Wt %, As-received)		
Total Moisture	25.62	18.21
Ash	6.03	4.24
Volatile Matter	28.14	32.42
Fixed Carbon	40.21	45.13
Higher Heating Value (Btu/lb)	9,179	9,840
Total Sulfur (Wt %)	0.85	0.84
SO_2 Emission Potential (lb/Mbtu)	1.85	1.69
Ash (lb/MBtu)	6.57	4.31
Hardgrove Grindability Index (HGI)	44	36
ULTIMATE ANALYSIS (Wt %, As-Received)		
Carbon	52.74	57.09
Hydrogen	3.45	3.93
Nitrogen	0.69	0.89
Sulfur	0.85	0.84
Ash	6.03	4.24
Oxygen	10.62	14.80
ASH FUSIBILITY (°F)		
(Reducing/Oxidizing)		
Initial Deformation	2125/2190	2280/2300
Softening	2150/2200	2295/2320
Hemispherical	2170/2220	2315/2335
Fluid	2230/2280	2325/2445
ASH COMPOSITION (Wt%)		
SiO_2	33.27	21.61
Al_2O_3	16.72	13.08
Fe_2O_3	5.73	5.68
CaO	15.48	24.12
MgO	3.54	4.18
Na_2O	0.86	1.52
K_2O	0.70	0.48
TiO_2	0.82	0.81
P_2O_5	1.26	0.08
SO_3	20.53	30.80

Following a new shipment of test coal, testing continued with the original 70/20/10 blend and opacity levels returned to acceptable levels; the 70/20/10 blend was used for the remainder of the baseline test program.

Because of problems encountered with coal availability, transport, and unit derates, the makeup of the alternate coal blend was varied on a couple of occasions before a final blend was determined for detailed characterization testing. After a period of boiler seasoning, a short test burn was initiated with the 85 WY/10 MT/5 PC blend. Early into this test burn, it became evident that not enough heat was being extracted from the boiler; as a result, the unit had to be derated by ten percent. King plant management decided not to attempt the 90 WY/10 MT blend, as they expected that this would only increase the derate. The CQE test contractors, in conjunction with NSP, decided to continue alternate coal testing with a blend of 93 percent Wyoming coal (obtained from NERCO Coal Corporation's Antelope Mine in Converse County, Wyoming) and seven percent petroleum coke, which allowed the unit to operate at normal load. The alternate coal testing was then carried out according to the designed test matrix.

Test results and conclusions from the King field test are summarized below:

- Primary superheater, secondary superheater and furnace water walls saw the largest change in relative heat transfer with no wall blowers.
- Sootblowers were effective in restoring heat absorption/temperature rise at the end of the slagging test.
- Furnace water wall temperature rise and NO_x emissions correlate well with furnace exit gas temperatures.
- P-max calculated FEGT correlated well with measured FEGT.
- Calculated cleanliness factors did not correlate well with section water temperature rise for short-term tests.
- Two coal blends were tested in detail: a 70/20/10 percent of Wyoming/ Montana/Pet-Coke baseline blend, and a 93/7 percent Wyoming/Pet-Coke alternate coal blend. Limited testing was performed firing a 95/5 percent blend of Wyoming/Pet-Coke blend but was not selected as the alternate coal blend because of ESP problems.
- The blended coal analyses were similar. Differences in ash sodium, sulfur, and ash concentrations, however, were large enough to produce significant differences in boiler and ESP performance.
- King Unit 1 was originally designed for bituminous coal firing. Since converting to coal blends similar to those above, the unit has occasionally experienced significant generating limitations as a result of high temperature fouling of

internal boiler surfaces and high opacity levels. Results from the CQE field test were used to determine root causes of these problems and formed the technical basis for recommendation to NSP that may lead to elimination of the problem in the future.

- King Unit 1 was the only cyclone-fired boiler tested in the CQE project. Combustion conditions from cyclone-to-cyclone and uniformity in the main furnace was found to be very consistent. Excess O_2 concentrations were very uniform (i.e., <5 percent variation) in the main furnace and at the economizer exit. Similarly, gas temperatures in the main furnace, below the level that gas tempering air is introduced, were uniform (i.e., <±25 °F variation). Localized, non-ideal combustion conditions were not observed, and accordingly, not considered to be a major contributor to localized fouling problems of the boiler.

- A new method was developed by the field test team to measure the flame ignition points and thermal profiles inside the cyclones. It may also be used to establish similar air, fuel, and thermal conditions among the cyclones. It may also be used as a troubleshooting technique to identify problematic operation in a multi-cyclone boiler.

- Peak temperatures inside the cyclones were approximately 2,900 °F for the baseline and alternate coal blends. Gas temperatures in the main furnace and through the convection passes, however, increased by 100-200 °F when the petroleum coke fraction of the coal blend was reduced from 10 to 5 percent. Gas temperatures as high as 2,700 °F were observed in the main furnace below the gas tempering ports. The field test team postulated (it could not be directly confirmed) that this was the result of an increase in coal particle combustion in the main furnace, downstream from the cyclones. This is believed to occur because of incrementally higher coal throughput on a mass basis and runnier slag inside the cyclones with the lower petroleum coke concentrations.

  The higher temperature operation did not result in an increase in water wall slagging or uniform fouling across the high temperature convection section of the boiler.

- Gas temperature profiles downstream from the gas tempering ports entering the secondary superheater were not uniform. The profile was typically depressed toward the center of the boiler and higher at the side walls. This is believed to be the result of non-uniform flow and temperature of the recirculated flue gas flowing through the nine gas tempering ports. This non-uniform flow is believed to be the major cause to localized fouling of the secondary superheater. Large, tenacious deposits (not removable with soot blowers) have been observed to grow immediately downstream of the gas tempering ports near the boiler sidewalls when the gas temperature exceeds 2,300 °F. The average gas temperature above the gas tempering ports was about 2,100 °F and 2,200 °F for the baseline and alternate coal blends, respectively. Thus, when firing blends having lower petroleum coke concentrations, the margin for fouling of the superheater is reduced, and the potential for problems induced by non-uniform gas tempering is increased significantly. If the gas tempering system were upgraded by eliminating the non-uniform distribution of gas to the ports, increasing the available total flow of gas, and/or reducing the recirculated flue gas temperature, then the boiler may be able to fire subbituminous coals having lower petroleum coke concentrations without major fouling episodes. Accordingly, the field test team has recommended to NSP, that potential means for upgrading the gas tempering system be investigated.

- The particle mass entering the King ESP was lower by a factor of two than would be expected with the same coal burned in a PC boiler. A reduced ESP inlet mass loading is typical of cyclone boilers.

- SO_3 concentrations were typically <0.1 ppm for both coals.

- Fly ash electrical resistivity was moderate, approximately 1×10^{10} ohm-cm, despite the low concentration of SO_3. Resistivity for the alternate coal was approximately half an order of magnitude lower than that for the baseline coal.

- Because of the compressibility of the fly ash, in situ resistivity measurements produced questionable results. That is, depending on the compactness of the fly ash sample, the measured resistivity was found to vary by up to two orders of magnitude. It is not understood, whether this is a characteristic of fly ash from cyclone boiler, the specific coal blends tested, or both. Accordingly, the resistivity noted above was based on laboratory measurements and corroborated by computer modelling using the electrical conditions of the ESP.

- Electrical conditions in the precipitator were good; there was no evidence of back corona.

- The particle size distribution of the ESP inlet had approximately two times as many particles that were smaller than 0.5 microns for the alternate coal than that for the baseline coal. The number of one micron particles, the primary contributor to opacity, was approximately the same for both coals.

- The measured collection efficiency for particles of approximately one micron in diameter were 95 percent and 75 percent for the alternate and baseline coals, respectively. Thus, the percentage of one micron particles penetrating the precipitator for the baseline coal was about five times that for the alternate coal. The corresponding opacities were 15 percent and 8 percent for the baseline coal and alternate coals, respectively.

- The sodium concentration of the fly ash entering the ESP was approximately one percentage point higher for the alternate coal than for the baseline coal. The difference is believed to account for the differences in small-particle size distributions, resistivity, and fundamental collection efficiencies of one-micron particles.

- The Wyoming coals tested at King Unit 1 had uncharacteristically high concentrations of sodium as compared to other coals from the Powder River Basin. If these other low-sodium coals (e.g., Black Thunder Mine) were fired at King, the probability for high opacity and generating limitations increases significantly. In such instances, SO_3 conditioning may be an effective countermeasure for controlling opacity.
- Mass emissions were approximately 0.025 and 0.035 lb/MBtu for the baseline and alternate coals, respectively, even though the inlet mass loadings were 30 percent lower for the alternate coal. This difference in outlet emissions was the result of poorer collection of large particles (i.e., > 5 microns) for the alternate coal. The poorer performance was attributable to non-ideal effects, such as rapping re-entrainment, sneakage, or hopper sluffing.
- The SoRI electrostatic precipitator model accurately predicted the opacity relationships that were observed. Because of the influence and variability of the non-ideal effects, the predictions of mass emissions were not very accurate.

4.3.5 APC Gaston Unit 5—Alabama and West Virginia Coals

Alabama Power Company's Gaston Unit 5 was the fourth of six test sites selected for utility boiler field testing under this program. It is located in Wilsonville, Alabama, and consists of a pressurized Combustion Engineering (CE) 880-MWg, twin-furnace, tangentially fired boiler that was commissioned in 1974. The boiler nameplate rating is 6.351×10^6 lb/hr of steam flow at 1000°F superheat temperature and 3,500 psig throttle pressure. The unit is a once-through design with a total of 56 burners for the two furnaces; each furnace section has seven burner elevations. The unit is equipped with a hot-side electrostatic precipitator with a design specific collection area of 287 ft^2/1000 acfm.

Burn tests were conducted to assess the coal quality impacts on boiler performance and emissions resulting from the burning of the typical, or baseline, coal and an alternate coal. The baseline coal for the test burn was a 2-percent sulfur Alabama coal from Pittsburg & Midway's North River Mine. The alternate coal was a 0.9 percent sulfur West Virginia coal from the Heartland Mine. Typical properties of the two coals are presented in Table 4-28. The reduced sulfur emission potential and lower grindability of the alternate coal was of major interest during the test burn.

Table 4-28
Test Coal Analyses–APC Gaston Unit 5

	Baseline Alabama (North River)	Alternate WV (Heartland)
PROXIMATE ANALYSIS (Wt %, As-received)		
Total Moisture	6.03	7.69
Ash	12.13	12.02
Volatile Matter	34.50	32.38
Fixed Carbon	47.34	47.91
Higher Heating Value (Btu/lb)	12,084	11,730
Total Sulfur (Wt %)	2.30	0.98
SO_2 (lb/Mbtu)	3.81	1.68
Ash (lb/MBtu)	10.04	10.25
Hardgrove Grindability Index (HGI)	57	48
ULTIMATE ANALYSIS (Wt %, As-Received)		
Carbon	67.00	65.28
Hydrogen	4.65	4.35
Nitrogen	1.46	1.29
Sulfur	2.30	0.98
Ash	12.13	12.02
Oxygen	6.43	8.39
ASH FUSIBILITY (°F)		
(Reducing/Oxidizing)		
Initial Deformation	2145/2400	2770/2800+
Softening	2255/2470	2800/2800+
Hemispherical	2315/2510	2800+/2800+
Fluid	2370/2560	2800+/2800+
ASH COMPOSITION (Wt%)		
SiO_2	38.29	55.78
Al_2O_3	28.53	25.84
Fe_2O_3	17.17	6.49
CaO	6.24	2.12
MgO	1.22	0.85
Na_2O	0.66	0.98
K_2O	1.73	1.92
TiO_2	1.25	2.00
P_2O_5	0.35	0.57
SO_3	4.63	1.26

The test burns at Gaston were conducted in two phases. Testing of the baseline coal occurred over the period from September 16 through October 11, 1991. The alternate coal test series was tested during October 10-29, 1992. The following sections summarize the equipment modifications and test conditions for the baseline test series.

As was the case at all the power plant test sites, a number of equipment modifications were required at APC Gaston to accommodate the field-testing effort. Labor and materials required to do this work were contributed to the project by the host utility (in this case, Alabama Power Company) and their parent company, Southern Company Services. A listing of equipment modifications and maintenance required at Gaston included the following:

- Repaired and cleaned all existing aspirator/doors.
- Installed four 6-in ID ports on each air heater outlet duct (total of 8).
- Modified 12 existing ports to 4-in ID aspirator ports on economizer outlet ducts.
- Installed 2-in standard pipe ports with ball valves at each pulverized coal/air pipe (total 56) leading to the burners.
- Provided new 6 x 12-in opening and installed port on the side of each economizer outlet duct for on-line LOI sampling equipment.
- Provided scaffolding on the eleventh floor for HVT traverses.
- Opened existing wall boxes at 534-ft elevation and provided 2 1/2-in standard diameter pipe with threaded cap on each side of the boiler furnace for large HVT traverses.
- Modified existing 2-in ports at the windbox to facilitate secondary air flow traverses.
- Repaired fuel-air and auxiliary air dampers.
- Cleaned ash taps at economizer and air preheater hoppers.
- Calibrated key plant instrumentation.
- Provided new penetrations at furnace side walls to accommodate view ports.
- Repaired sight glasses.
- Cleaned refractory from inside boiler for furnace penetrations.

- Enlarged existing furnace wall O_2 taps, and added additional taps at two elevations.

- Provided 12 chordal thermocouples at selected locations.

- Installed a flop gate and chute from the primary coal sampler to the ground, and provided a stone base around the sampler to accommodate raw-coal sampling during the test burns.

Following a brief series of diagnostic tests, the baseline coal test burn was conducted according the site test matrix. In addition to detailed emissions and performance characterization at full load, tests were performed at varying levels of load and excess air. Tests of specific interest to APC were performed to examine in more detail the slagging and carbon burnout characteristics of the coal when operating the unit under particularly demanding operating conditions.

Test results and conclusions from the Gaston field test are summarized below:

- During the baseline test, NO_x emissions increased with increasing unit load and varied from 0.53 lb/MBtu at 450 MW to 0.71 lb/MBtu at 920 MW.

- SO_2 emissions were approximately 3.7 lb/MBtu.

- CO emissions were less than 30 ppm.

- Unburned flyash carbon losses were approximately 1.0 percent. Unburned ash carbon losses were approximately 0.7 percent.

- Boiler efficiency increased with a decrease in load, increasing from 89.5 percent at 920 MW to 91.0 percent at 450 MW.

- Air heater leakages were 5.3 percent on the left and 8.1 percent on the right.

- The measured performance of the ESP was surprisingly good. ESP collection efficiency was over 99.5 percent with a particle emission rate of 0.03 lb/10^6 Btu and a stack opacity of 6 percent.

- The PM_{10} measurements indicated an emission rate for particles smaller than 10 μm of approximately 0.01 lb/10^6 Btu.

- A factor of three variation in the outlet emissions was observed in both the mass trains and PM_{10} measurements. The variation occurred in particles larger than 10 μm. Whether this was caused by rapping, reentrainment, or sampling problems is unknown.

- The particle size distribution of the fly ash entering the ESP was found to contain fewer fine particles than the typical bituminous coal. Fewer fine particles would tend to reduce stack opacity for a given ESP performance level.

- The sodium-depleted resistivity data indicated that resistivity of the ash could be in the low 10^{10} ohm-cm range at high load and close to 10^{11} ohm-cm at low loads. ESP performance would be affected by these resistivity levels.

- ESP voltage-current (V-I) curves indicated that the ESP electrical conditions are lower than anticipated with the projected resistivity. The unexpected limitations are either the result of underprediction of the resistivity by the depletion model, to mechanical problems in the ESP, or errors in measuring electrical conditions.

- The ESP model was unable to compute ESP performance levels as high as measured when using the actual electrical conditions as input. Better results were obtained using electrical conditions estimated from the ash resistivity. This suggested a review of ESP specifications and electrical measurements was needed.

4.3.6 NEP Brayton Point Unit 3–West Virginia Coals

New England Power's Brayton Point Unit 3 was the fifth of six test units selected for utility boiler field testing under this program and is located near Somerset, Massachusetts. Unit 3 is a 620 MWg horizontally opposed-fired B&W boiler equipped with cell burners. The unit is equipped with five MPS-89 mills feeding five columns of burners on each wall. The unit is a supercritical unit rated nominally at 4,050,000 lb/hr steam flow at a superheat and reheat temperature of 1,000 °F. Unit 3 was converted from oil to coal firing in 1982 and a new electrostatic precipitator with a specific collection area (SCA) of 580 ft^2/1,000 acfm was added at that time to improve ash collection and handling with coal-fired operation.

Burn tests were conducted to assess the coal quality impacts on boiler performance and emissions resulting from the burning of the typical, or baseline, coal and an alternate low sulfur coal. The baseline coal for the test burn was a 1.1 percent sulfur coal supplied by the Daltex Coal Corporation from Logan County, West Virginia. The alternate coal was a blend of 60 percent cleaned West Virginia coal from the Omar Mine (Omar Mining Company, Boone County) and 40 percent raw Daltex coal. The cleaned Omar Mine coal had a sulfur content of 0.8 percent. Typical properties of the two coals are presented in Table 4-29. The primary area of concern at Brayton Point was the potential impacts on fly ash resistivity and ESP performance as the result of anticipated reductions in SO_3 vapor.

New England Power conducted the baseline coal tests in August 1992, and the CQE field testing contractors performed the alternate coal tests in March 1993.

Table 4-29
Test Coal Analyses–NEP Brayton Point Unit 3

	Baseline WV (Daltex)	Alternate WV (Omar/Daltex)
PROXIMATE ANALYSIS (Wt %, As-received)		
Total Moisture	5.45	6.31
Ash	8.78	9.67
Volatile Matter	32.00	32.64
Fixed Carbon	53.77	51.38
Higher Heating Value (Btu/lb)	13,166	12,633
Total Sulfur (Wt %)	1.05	0.75
SO_2 (lb/Mbtu)	1.60	1.19
Ash (lb/MBtu)	6.67	7.65
Hardgrove Grindability Index (HGI)	76	43
ULTIMATE ANALYSIS (Wt %, As-Received)		
Carbon	70.65	70.94
Hydrogen	4.72	4.62
Nitrogen	1.33	1.31
Sulfur	1.05	0.75
Ash	8.78	9.67
Oxygen	8.03	6.40
ASH FUSIBILITY (°F)		
(Reducing/Oxidizing)		
Initial Deformation	2790/2800+	2800+/2800+
Softening	2800+/2800+	2800+/2800+
Hemispherical	2800+/2800+	2800+/2800+
Fluid	2800+/2800+	2800+/2800+
ASH COMPOSITION (Wt%)		
SiO_2	51.70	57.12
Al_2O_3	31.40	33.27
Fe_2O_3	8.70	3.16
CaO	1.00	1.51
MgO	0.89	0.93
Na_2O	0.44	0.24
K_2O	2.32	1.90
TiO_2	1.83	1.76
P_2O_5	0.11	0.22
SO_3	0.61	0.59

Following a brief series of diagnostic tests, the alternate coal test burn was conducted according to the unit test matrix. In addition to a detailed emissions and performance characterization at full load, tests were scheduled at varying levels of load and excess air. Tests of specific interest to New England Power were performed to examine in more detail the ash deposit formation, slagging, fouling, and carbon burnout characteristics of the coal when operating the unit under particularly demanding operating conditions.

Test results and conclusions from the Brayton Point Unit 3 field test are summarized below:

- Conversion of fuel sulfur to SO_2 ranged from 85 percent to 95 percent.
- Combustion diagnostics indicated an area of non-uniform combustion along the east wall of the boiler.
- Air in-leakage along the west wall of the economizer exit duct work was strongly suspected.
- Unit 3 NO_x emissions were strongly dependent upon firing rate as indicated by coal flow and furnace exit gas temperature.
- Full-load NO_x emissions with the baseline and alternate coal were:

Baseline	800 ppm (1.09 lb/MBtu)
Alternate	900 ppm (1.23 lb/MBtu)

- The lower grindability and Btu content of the alternate coal required five mill operation to reach full load.
- NO_x emissions dropped to 660 ppm (0.90 lb/MBtu) at 350 MW with the reduced firing rate in spite of an increase in O_2 to 5.5 percent.
- Full-load NO_x emissions with 60 Omar/40 Daltex were essentially identical to the 100 percent Daltex.
- Ash LOI content with all coals was less than 3.2 percent, even at minimum O_2 levels.
- Ash LOI at normal O_2 levels was typically one to 1.2 percent with five mill operation at normal O_2 levels, but increased to two percent with four mill operation.
- The collection efficiency of the Unit 3 Research Cottrell (RC) ESP system averaged 99.78 percent with an average emission rate of 0.016×10^6 lb/Btu. The performance of the Koppers ESP was very poor at 61 percent efficiency.

- The performance of the RC ESP was significantly better on the second day of testing with a collection efficiency of 99.92 percent and emission rate of 0.006 × 10^6 lb/Btu. This was thought to be a residual effect of the recent startup.

- The change in ESP performance between the two test days could not be correlated with any measured parameter. Non-ideal effects related to some type of re-entrainment process must have been responsible.

- Vapor-phase SO_3 concentrations of one to two ppm were measured at the inlet to the Koppers ESP. This result was supported by the sub-dewpoint temperature measured at the inlet of the east-side RC ESP, suggesting that very little vapor should remain there.

- At the Koppers inlet, the fly ash resistivity was measured at 7 × 10^{11} ohm-cm. The resistivity on the east-side of the RC ESP may have been somewhat higher because of the loss of SO_3. This is high resistivity and would be expected to impose a severe limitation on the electrical performance of the ESP.

- The lab and predicted resistivity data indicated that the Daltex fly ash should be susceptible to SO_3 conditioning. However, the low gas temperatures on the East side of the RC ESP and the very low alkaline content of the Daltex ash may make conditioning difficult.

- Back corona was occurring in the RC ESP above 12 to 30 nA/cm^2 which is consistent with moderately high resistivity. A few of the ESP fields were operating slightly into back corona. Increasing power input to the fields that were not in back corona should improve performance.

- Some type of automatic back corona avoidance control, such as intermittent energization, should improve performance of this ESP.

- An ESP model sneakage and reentrainment factor four times greater than normal were required to simulate the RC ESP, which indicates either erroneous electrical data or severe re-entrainment in the ESP.

- The power-off-rapping system may have been responsible for the higher than expected emissions. Comparative tests should be performed to determine if emissions are reduced without the system.

4.3.7 NEP Brayton Point Unit 2--Virginia and Kentucky Coals

New England Power's Brayton Point Unit 2 is the sixth of six test units selected for utility boiler field testing under this program and is located near Somerset, Massachusetts. Unit 2 is a 250 MWg tangentially-fired, twin-furnace ABB CE unit. The unit is equipped with four CE T-Series mills feeding four separate burner elevations. The unit is a subcritical unit rated nominally at 1,675,000 lb/hr steam flow at a superheat and reheat temperature of 1,000°F. Unit 2 was converted from oil to coal firing in 1982 and a new electrostatic precipitator with a specific collection area (SCA) of 560 $ft^2/1{,}000$ acfm was added at that time to improve ash collection and handling with coal-fired operation.

Burn tests were conducted to assess the coal quality impacts on boiler performance and emissions resulting from the burning of the typical, or baseline, coal and an alternate low sulfur coal. The baseline coal for the test burn was a low sulfur coal obtained from Island Creek Coal Company's Pocahontas Mine located in Buchanan County, Virginia. The alternate coal was a cleaned coal from MAPCO's Pontiki Mine located in Martin County, Kentucky. Typical properties of the two coals are presented in Table 4-30.

New England Power conducted the baseline coal tests in May 1991, and the CQE field testing contractors performed the alternate coal tests in April 1993. Following a brief series of diagnostic tests, the alternate coal test burn was conducted according to the unit test matrix. In addition to a detailed emissions and performance characterization at full load, tests were scheduled at varying levels of load and excess air. Tests of specific interest to New England Power were performed to examine in more detail the ash deposit formation, slagging, fouling, and carbon burnout characteristics of the coal when operating the unit under particularly demanding operating conditions.

Test results and conclusions from the Brayton Point Unit 2 field test are summarized below:

- SO_2 emissions for the two test coals were:
  Pocahontas (Baseline) 0.95 lb/MBtu
  Pontiki (Alternate) 0.75 lb/MBtu

- Conversion of fuel sulfur to SO_2 averaged 91 percent with Pontiki (not determined for the baseline Pocahontas test).

- Combustion diagnostics indicated a high-O_2 and a high-NO_x region on the left (east) side of the boiler.

- The variations in the "as-found" combustion condition conditions across the boiler were: O_2 1.8 to 4.6%
  NO_x 380 to 550 ppm (0.52 to 0.75 lb/MBtu)

- A custom multi-point O_2 analyzer was used to bias the air registers to offset the burner pipe fuel maldistribution.

- The variations in combustion conditions after optimization were:
  O_2 2.2 to 2.6%
  NO_x 390 to 410 ppm (0.52 to 0.56 lb/MMBtu)

Table 4-30
Test Coal Analyses--NEP Brayton Point Unit 2

	Baseline VA (Pocahontas)	Alternate KY (Pontiki)
PROXIMATE ANALYSIS (Wt %, As-received)		
Total Moisture	6.31	8.90
Ash	4.75	7.47
Volatile Matter	17.59	30.97
Fixed Carbon	71.34	52.66
Higher Heating Value (Btu/lb)	13,992	12,508
Total Sulfur (Wt %)	0.78	0.73
SO_2 (lb/Mbtu)	1.11	1.17
Ash (lb/MBtu)	3.39	5.97
Hardgrove Grindability Index (HGI)	94	42
ULTIMATE ANALYSIS (Wt %, As-Received)		
Carbon	80.79	71.19
Hydrogen	3.88	4.43
Nitrogen	1.21	1.19
Sulfur	0.78	0.73
Ash	4.75	7.47
Oxygen	2.28	6.09
ASH FUSIBILITY (°F)		
(Reducing/Oxidizing)		
Initial Deformation	2370/NA	2795/2800+
Softening	2800+/2800+	2800+/2800+
Hemispherical	2800+/2800+	2800+/2800+
Fluid	2800+/2800+	2800+/2800+
ASH COMPOSITION (Wt%)		
SiO_2	37.65	55.35
Al_2O_3	24.90	28.40
Fe_2O_3	14.47	6.04
CaO	8.01	2.56
MgO	1.73	0.79
Na_2O	1.04	0.60
K_2O	1.67	1.72
TiO_2	1.27	1.80
P_2O_5	0.22	0.31
SO_3	7.91	1.56

- Full-load NO_x emissions with the Pontiki coal were typically 400 ppm (0.55 lb/MBtu).

- The NO_x sensitivity to O_2 was approximately 55 ppm/1 percent O_2 change.

- NO_x emissions increased at lower loads to 525 ppm (0.72 lb/MBtu), primarily because of increased O_2 levels (7.5 percent at 113 MW).

- NO_x emissions were reduced 38 percent with simulated over-fire-air (OFA) operation with a 50 MW derate and poor lower furnace combustion conditions.

- No adverse furnace combustion conditions or ash deposition were noted with the Pontiki coal.

- Ash LOI increased dramatically at O_2 levels less than 3 percent at the economizer exit.

- The performance of the Koppers ESP on Unit 2 was substantially better than that of Unit 3 with collection efficiency of 92.6 percent. The collection efficiency of the RC ESP was very low with an average below 90 percent. The combined effect of the total system was 99.29 percent efficiency with an emission rate of 0.036×10^6 lb/Btu. This is three times higher penetration of the total ESP system despite the higher SCA of Unit 2.

- No SO_3 vapor was found in the flue gas at the inlet to the Koppers ESP. The acid apparently reacted with the increased alkaline components of the fly ash.

- The electrical conditions of the ESP were severely degraded by the ash resistivity with back corona occurring at 3 nA/cm^2. The operating points of the ESP transformer-rectifier (T-R) sets were well into back corona, which would result in some degradation of performance (the function of the ESP power supply is to deliver and maintain optimum electrical conditions for charging and collecting fly ash particles; to achieve this, the T-R sets must provide the highest possible useful corona power without causing arc-over). Also, all power input to the ESP above the onset of back corona was wasted.

- The reason for the difference in operation in Units 2 and 3 with the same in-situ resistivity was not apparent, but may have been related to the time that the units had been on line.

- The ESP model matched the performance of the Koppers ESP with the standard set of non-ideal conditions, indicating that the unit performed as expected. However, a sneakage and re-entrainment factor 6.5 times larger than normal was required to match the performance of the RC ESP. Some of the disagreement may have been caused by the back corona operation, but as with Unit 3, it is believed that excessive rapping reentrainment caused by the power-off-rapping was likely to be a significant part of the cause.

5.0

ENVIRONMENTAL PERFORMANCE

One of the first steps in this project was the preparation of an Environmental Information Volume (EIV). The EIV was prepared to facilitate the U.S. Department of Energy's compliance with the National Environmental Policy Act (NEPA) of 1969. Discussions of the environmental, health, safety, and socioeconomic impacts associated with each utility field test site were included in the EIV.

Additionally, as a Clean Coal Technology project, Development of the Coal Quality Expert (CQE) is subject to the compliance procedures of the Department of Energy (DOE). One of these requirements was the development and implementation of an approved Environmental Monitoring Plan (EMP). The purposes of the EMP are to:

- Document the extent of compliance monitoring activities (i.e., those monitoring activities conducted to meet permit requirements);
- Confirm the specific environmental impacts predicted in the National Environmental Policy Act documentation (EIV); and
- Establish an information base for the assessment of the environmental performance of the technology demonstrated by the project.

An EMP was prepared that covered these issues for all six utility field test sites. Two types of environmental monitoring were conducted during the field tests to satisfy the requirements of the EMP: compliance monitoring and supplemental monitoring. Compliance monitoring is required by local, state, and federal environmental agencies to demonstrate compliance with applicable regulations and permits; supplemental monitoring includes specific test measurements beyond compliance monitoring required to develop the database for the Coal Quality Expert and associated documentation.

Finally, Environmental Monitoring Reports (EMR) were prepared throughout the course of the project and a final EMR was prepared for each field test site. This final report summarizes the EMR for all six sites.

5.1 Environmental Monitoring--PSO Northeastern Unit 4

CQE field tests were conducted at Public Service Company of Oklahoma's (PSO) Northeastern Unit 4 in 1990 to assess the impacts on boiler performance and emissions of a baseline coal and two alternate coal blends. Table 5-1 presents the source (or permit) requirements for Northeastern Unit 4. This involves the monitoring of parameters that contribute to the waste streams (i.e., gaseous, aqueous, and solid waste and by-product streams) released into the atmosphere. Table 5-2 lists the types of samples and measurements needed to characterize the operating conditions at Northeastern Unit 4. All monitoring of this type is supplemental and remained essentially constant for all six utility field tests.

Table 5-1
Environmental Monitoring Requirements PSO's Northeastern Plant (Source Monitoring)

Stream	Parameter	Location	Frequency	Monitoring*
Gaseous	Opacity	In Stack	Continuous	C
	SO_2	In Stack	Continuous	C
	SO_2	Boiler Exit	Continuous	S
	NO	Boiler Exit	Continuous	S
	NO_x	In Stack	Continuous	C
	NO_x	ESP Inlet	1 per Test	S
	CO	Boiler Exit	Continuous	S
	CO_2	Boiler Exit	Continuous	S
	O_2	Boiler Exit	Continuous	S
	Particulate Matter	ESP Outlet	1 per Test	S
Aqueous	Flow	Outfalls 001, 002, 003	Continuous	C
	Temperature	Outfalls 001, 003	Continuous	C
	Chlorine	Outfalls 001, 003	1 per Week	C
	Total Susp. Solids	Outfalls 002, 004	1 per Week	C
	Oil & Grease	Outfall 002	1 per Week	C
Solid				
Feed Coal	Proximate Analysis	Feeder Inlet	2 per Day	S
	Ultimate Analysis	Feeder Inlet	2 per Day	S
	Calorific Value	Feeder Inlet	2 per Day	S
	Mineral Ash	Feeder Inlet	2 per Day	S
	Ash Fusion Temp.	Feeder Inlet	2 per Day	S
	Grindability	Feeder Inlet	2 per Day	S
	Mass Flow	Coal Flow Integrators	1 per Hour	S
Bottom Ash	Carbon Content	Bottom Ash Hopper	1 per Test	S
	Sulfur Content	Bottom Ash Hopper	1 per Test	S
Fly Ash	Carbon Content	Fly Ash Hopper	1 per Test	S
	Sulfur Content	Fly Ash Hopper	1 per Test	S

* C= Compliance S=Supplemental

Table 5-2
Monitoring of Process and Operating Conditions (Supplemental)

Category	Type
Feed Coal	Raw Coal Sampling Coal Flow Handling
Mills	Pulverizer Power Mill Vibration Mill Rejects PC Sample Dirty Pitot
Boiler	Feedwater Superheater/Reheat Attemperation Steam Temperature Control Boiler Metal Temperature Air Heater Temperature Flue Gas Analysis Mill Differential Precipitator Hopper Pluggage
Gas Flows	Primary Air Combustion Air
Performance	Bottom Ash Fouling Fly Ash Flame Stability Furnace Draft Air Heater Differential Pressures
Precipitator	Power - V/I Curves Flue Gas Flow Inlet Dust Loading/Size Fly Ash Resistivity Collection Efficiency Rapper Control System Stratification at Inlet

Northeastern Unit 4 is required to perform continuous, in-stack monitoring of opacity, sulfur dioxide, and nitrous oxide emissions; there are no ambient monitoring requirements at this site. The emissions limits for these three parameters are as follows:

Opacity	20 percent
SO_2	1.2 lbs/MBtu
NO_x	0.7 lbs/MBtu

No excess emissions of SO_2 or NO_x were recorded at Northeastern Unit 4 during the test periods. Opacities exceeded 20 percent on a few occasions, generally as a result of sootblowing or unit shutdown/startup to repair a boiler tube failure. On one occasion, the opacity limit was exceeded as a result of an ESP field temporarily being taken out of service to install control transformers for the test burn.

The National Pollutant Discharge Elimination System (NPDES) permit for Northeastern Unit 4 requires compliance monitoring for four outfalls. Outfalls 001 and 004 discharge into the Verdigris River while 002 and 003 empty into Fourmile Creek. Fourmile Creek flows directly into the Verdigris River. The parameters monitored included flow, temperature, chlorine, total suspended solids, and oil and grease. All discharge measurements were well within permit requirements during the field test period.

5.2 Environmental Monitoring--MPC Watson Unit 4

Mississippi Power Company's (MPC) Watson Unit 4 was the second utility field test site for the CQE project. Field tests were conducted during October and November 1990. Watson Unit 4 is a coal test unit for MPC, which conducts approximately one coal test burn each quarter using this unit. Because Watson Unit 4 is considered a test bed for MPC, it has burned many candidate coals over a period of several years, yielding both acceptable and unacceptable performance.

Table 5-3 summarizes the environmental monitoring requirements for the Watson Unit 4 test program, and Table 5-4 lists supplemental testing beyond that of Table 5-2 that was conducted for the Watson Unit 4 test program. Table 5-3 presents the source (or permit) requirements; this involves the monitoring of parameters that contribute to the waste streams (i.e., gaseous, aqueous, and solid waste and by-product streams) released into the environment. Mississippi Power Company's Watson Plant has a total of six permitted emission points. Five of these points are associated with the five boiler units. The final point is associated with a combustion turbine. The permitted point for Unit 4 is emission point 004.

The following pollutants emanating from this emission point are monitored: opacity, sulfur dioxide, and particulate matter. In-stack instrumentation is used to continuously monitor the plume's opacity. Sulfur dioxide and particulate matter are monitored through coal quality analyses. The percent sulfur, percent ash, heating value, and approximate tonnage of fuel fired is reported quarterly. There are no ambient monitoring requirements at this site.

Table 5-3
Environmental Monitoring Requirements at MPC Watson Unit 4 (Source Monitoring)

Stream	Parameter	Location	Frequency	Monitoring*
Gaseous	Opacity	In Stack	Continuous	C
	Opacity	In Stack	1 per Test	S
	SO_2	Boiler Exit	Continuous	S
	SO_3	ESP Inlet	1 per Test	S
	NO	Boiler Exit	Continuous	S
	NO_x	ESP Inlet	1 per Test	S
	CO	Boiler Exit	Continuous	S
	CO_2	Boiler Exit	Continuous	S
	O_2	Boiler Exit	Continuous	S
	Particulate Matter	ESP Inlet	1 per Test	S
	Particulate Matter	ESP Outlet	1 per Test	S
Aqueous	Flow	Outfalls 001,002,003,004,005,012	Continuous	C
	Free Available Chlorine	Outfalls 002,004	1 per Week	C
	pH	Outfalls 001,002,003,004,005,012	1 per Week	C
	Temperature	Outfalls 001,002	Continuous	C
	Total Copper & Iron	Outfall 012	1 per Day	C
	Oil and Grease	Outfalls 003,005	1 per Day	C
	Total Susp. Solids	Outfalls 003,005	1 per Day	C
Solid				
Feed Coal	Proximate Analysis	Feeder Inlet	2 per Day	S
	Ultimate Analysis	Feeder Inlet	2 per Day	S
	Calorific Value	Feeder Inlet	2 Per Day	S
	Mineral Ash	Feeder Inlet	2 Per Day	S
	Ash Fusion Temp.	Feeder Inlet	2 per Day	S
	Grindability	Feeder Inlet	2 per Day	S
	Mass Flow	Coal Flow Integrators	1 per Hour	S
Bottom Ash	Carbon Content	Bottom Ash Hopper	1 per Test	S
	Sulfur Content	Bottom Ash Hopper	1 per Test	S
Fly Ash	Carbon Content	Fly Ash Hopper	1 per Test	S
	Sulfur Content	Fly Ash Hopper	1 per Test	S

* C = Compliance S = Supplemental Monitoring

Table 5-4
Monitoring of Process and Operating Conditions at MPC Watson Unit 4 (Supplemental)

Category	Type
Special Tests (high load)	Flue Gas Traverse (24 point)
	Particle Color Analysis (24 point)
	Total Heat Flux (twice)
	Furnace Wall Atmospheres
	Furnace Exit Gas Temperature
	Furnace Velocity
	Sootblowing
	Furnace Video (Weyerhauser)
	Optical Pyrometry (PSI)
Special Tests (maximum load)	Slagging (long test)
Other Tests (twice daily)	Slagging (visual)
	Boiler Tube Cleanliness
Other Tests (low load)	Backend Corrosivity
Other Tests (continuous)	Ash Carbon
	Opacity
Special Tests	SO_3
Special Tests	Fouling

The opacity levels during the initial test period ranged between 10 and 20 percent but suddenly increased to 25 to 35 percent towards the latter part of the baseline coal test and remained high throughout the alternate coal test period. The opacity increase was attributed to a 22-percent reduction in specific collection area, from 126 to 98 ft^2/1,000 acfm, that was caused by outages of three of the twelve ESP bus sections.

Sulfur dioxide emissions were approximately five percent higher for the higher sulfur alternate coal than for the baseline coal. Particulate emissions were higher during the alternate coal test as the result of the outages of three of the 12 ESP bus sections.

The NPDES permit for the Watson Plant specifies six outfalls: one is an intake canal (001), two discharge into the ash pond (004 and 012), and the other three discharge directly into the surrounding environment (002, 003, and 005). The primary outfall of concern is 002. This discharge is responsible for approximately 96 percent of all the aqueous wastewater discharged to the environment from the site. The parameters monitored included flow, temperature, pH, free available chlorine, total copper, total iron, oil and grease, and total suspended solids. All discharge measurements were well within permit requirements during field testing.

5.3 Environmental Monitoring–NSP King Unit 1

Northern States Power Company's (NSP) King Unit 1 is a summer base-loaded unit. Baseline coal testing was conducted during May 13-31, 1991, with the alternate coal tests being conducted during November 7-22, 1991. Table 5-5 summarizes the environmental monitoring requirements for King Unit 1. Supplemental testing was the same as that presented in Table 5-2. Table 5-5 presents the source (or permit) requirements, involving the monitoring of parameters that contribute to the waste streams released into the environment (i.e., gaseous, aqueous, and solid waste and by-product streams). Plant King's air emissions are permitted by the Minnesota Pollution Control Agency (Permit No. 202G-86-OT-1). Plant King conducts continuous in-stack monitoring of opacity, SO_2, and diluent (O_2) emissions in its primary 785-foot stack. In addition, coal quality is analyzed daily to further demonstrate compliance with SO_2 emission limits. There are no ambient air monitoring requirements at King Unit 1.

The SO_2 emission limit for the unit is 3.0 lb/MBtu on a 30-day rolling average; there were no excess emissions reported during the test program. The opacity limit for the unit is 20 percent (in a one-minute average). There were occurrences of excess opacity levels at the outset of the baseline test program (May 13-15, 1992) that were believed to be the result of an atypical shipment of coal (low sulfur and sodium content). The only excursions reported during the fourth quarter of 1991 occurred after the completion of the alternate coal test burn, and these were a result of either a unit shutdown or the boiler being cleaned while the unit was off line.

The NPDES permit for King Unit 1 (Permit No. MN0000825) specifies five outfalls that collectively discharge into an adjacent lake. Table 5-5 lists the specific outfalls; the parameters that are monitored include flow, temperature, total suspended solids, turbidity, and pH. Outfall D010--condenser cooling water discharge--accounts for over 98 percent of all waste water discharge and is monitored for flow and temperature on a continuous basis. All discharge measurements were within permit requirements during the test periods.

Because slag from by King Unit 1 is sold instead of being sent for disposal, quarterly leach testing is performed. No other compliance monitoring of solid waste or by-product streams is required at King Unit 1. In accordance with Minnesota Pollution Control Agency permit SW-356, Northern States Power monitors the slag on a routine basis to determine its suitability for use as an admixture and/or fill material. Monthly samples are collected and composited to form one quarterly sample that is analyzed using Method 1312 synthetic precipitation leach test for soils. The purpose of this test is to determine the water solubility of various trace metals. The results of the leach tests are then compared to performance standards (in this case, primary and secondary drinking water standards) to determine their suitability for utilization.

The leach test results for the first three quarters met the performance standards. The test on the fourth quarter composite sample showed that the sulfate concentration exceeded the standard. The sulfate concentration of this sample was four to six times greater than those found in samples from the previous three quarters (260 mg/l versus 40-62 mg/l). At the time of this report, it had not been determined whether the fourth quarter sample had been contaminated.

Table 5-5
Environmental Source Monitoring Requirements for Northern States Power Company's Plant King Unit 1

Stream	Location	Parameter	Frequency	Monitoring*
Gaseous	In Stack	Opacity	Continuous	C
		SO_2	Continuous	C
		O_2	Continuous	C
	Boiler Exit	SO_2	Continuous	S
		NO	Continuous	S
		CO	Continuous	S
		CO_2	Continuous	S
		O_2	Continuous	S
	ESP Inlet	SO_3	1/Test	S
		NO_x	1/Test	S
		Particulates	1/Test	S
	ESP Outlet	Particulates	1/Test	S
Aqueous	Outfall D010	Flow	Continuous	C
		Temperature	Continuous	C
	Outfall D011	Flow	1/Day	C
		Oil & Grease	1/Day	C
		Total Iron	1/Day	C
	Outfall D012	Flow	1/Week	C
		Total Susp Solids	1/Week	C
		Turbidity	1/Week	C
		Oil & Grease	1/Week	C
		pH	Continuous	C
	Outfall D013	Flow	Continuous	C
	Outfall D014	Flow	2/Month	C
Solid				
Ash	Ash Landfill	Volume of Ash	1/Day	C
Feed Coal	Feeder Inlet	Proximate Analysis	2/Day	S
		Ultimate Analysis	2/Day	S
		Calorific Value	2/Day	S
		Mineral Ash	2/Day	S
		Ash Fusion Temp	2/Day	S
		Grindability	2/Day	S
	Coal Flow Integrators	Mass Flow	1/Hour	S
Bottom Ash	Bottom Ash Hopper	Carbon Content	1/Test	S
		Sulfur Content	1/Test	S
Fly Ash	Fly Ash Hopper	Carbon Content	1/Test	S
		Sulfur Content	1/Test	S

*C = Compliance S = Supplemental

5.4 Environmental Monitoring--APC Gaston Unit 5

Diagnostic and baseline coal testing occurred from August 20 to October 31, 1991, at Alabama Power Company's Gaston Unit 5. The alternate coal test series was conducted from September 29 to October 25, 1992.

Table 5-6 summarizes the environmental monitoring requirements for Alabama Power Company's Plant Gaston Unit 5. Supplemental testing was the same as that presented in Table 5-2. Table 5-6 presents the source (or permit) requirements, involving the monitoring parameters that contribute to the waste streams released into the environment (gaseous, aqueous, solid waste and by-product streams). Plant Gaston's Unit 5 air emissions are permitted by the Alabama Pollution Control Agency (Permit No. 4-11-0005-Z005). Plant Gaston conducts continuous in-stack monitoring of opacity, SO_2, and diluent (O_2) emissions in its primary stack. In addition, coal quality is analyzed daily to further demonstrate compliance with SO_2 emission limits. The permit requires that ambient air monitoring for sulfur dioxide be conducted at three offsite locations.

The SO_2 emission limit for the unit is 3.0 lb/MBtu on a 30-day rolling average; there were no excess emissions reported during the test program. Opacity limit for the unit is 20 percent (one-minute average). Several opacity occurrences arose. The majority of these were related to load changes and electrostatic precipitator problems.

Approximately two thirds of total net excess opacity periods (i.e., total excess emission periods minus the number of excess emission periods caused by the startup or shutdown of the unit) were attributed to unit load changes, and approximately one third were the result of electrostatic precipitator malfunctions.

The NPDES permit for Gaston Unit 5 (Permit No. AL0003140) specifies four outfalls that discharge to a natural receiving water: 001, 002, 004, and 025. Table 5-6 lists the specific outfalls; the parameters that are monitored include flow, temperature, total suspended solids, turbidity, and pH. Two of the four outfalls (001 and 002), which are condenser cooling water discharges, account for over 98 percent of all waste water discharge, and are monitored for flow, intake temperatures, discharge temperatures, total residual chlorine, and the time of chlorine discharge. All discharge measurements were within permit requirements during the test periods.

Table 5-6
Environmental Source Monitoring Requirements for Alabama Power Company's Plant Gaston Unit 5

Stream	Location	Parameter	Frequency	Monitoring*
Gaseous	In Stack	Opacity	Continuous	C
	Coal Analysis	SO_2	1/Week	C
	Boiler Exit	SO_2	Continuous	S
		NO	Continuous	S
		CO	Continuous	S
		CO_2	Continuous	S
		O_2	Continuous	S
	ESP Inlet	SO_3	1/Test	S
		NO_x	1/Test	S
		Particulates	1/Test	S
	ESP Outlet	Particulates	1/Test	S
Aqueous	Outfall 001, 002	Flow	1/Day	C
		Intake/Discharge	1/Day	C
		Total Residual Chlorine	1/Day	C
		Time of Chlorine Discharge	1/Day	C
	Outfall 004	Flow	1/Month	C
		pH	1/Day	C
		Oil & Grease	1/Month	C
		Total Suspended Solids	1/Month	C
	Outfall 025	Flow	N/A	C
		pH	N/A	C
Solid				
Feed Coal	Feeder Inlet	Proximate Analysis	2/Day	S
		Ultimate Analysis	2/Day	S
		Calorific Value	2/Day	S
		Mineral Ash	2/Day	S
		Ash Fusion Temp	2/Day	S
		Grindability	2/Day	S
	Coal Flow Integrators	Mass Flow	1/Hour	S
Bottom Ash	Bottom Ash Hopper	Carbon Content	1/Test	S
		Sulfur Content	1/Test	S
Fly Ash	Fly Ash Hopper	Carbon Content	1/Test	S
		Sulfur Content	1/Test	S

*C = Compliance S = Supplemental

5.5 Environmental Monitoring–NEP Brayton Point Unit 3

The fifth utility field test site for the CQE project was New England Power Service Company's (NEP) Brayton Point Unit 3. Table 5-7 summarizes the environmental monitoring requirements for Brayton Point Unit 3. Supplemental testing was the same as that presented in Table 5-2. Table 5-7 presents the source (or permit) requirements, involving the monitoring parameters that contribute to the waste streams released into the environment (gaseous, aqueous, solid waste and by-product streams).

Brayton Point Station's Unit 3 air emissions are permitted by the Massachusetts Department of Environmental Protection (DEP). Brayton Point station conducts continuous in-stack monitoring of opacity, SO_2, and diluent (O_2) emissions in its primary stack. In addition, coal quality is analyzed daily to further demonstrate compliance with SO_2 emission limits. The permit requires that ambient air monitoring for sulfur dioxide be conducted at three offsite locations.

The ambient SO_2 emission limit for the station is 120 parts per billion (ppb) on a three-hour rolling average. The opacity limit for the unit is 20 percent (one-minute average). All continuous emission monitoring reports for the test period are on file and available at NEP and the Massachusetts DEP.

The NPDES permit for Brayton Point Station (Permit No. MA0003654) specifies 11 outfalls that discharge to a natural receiving water. Table 5-7 lists the specific outfalls, measured parameters, and monitoring frequency. The outfalls are analyzed for flow rate, intake and discharge temperatures, total residual organics, total suspended solids, oil and grease, and the metals: copper, iron, nickel, and zinc. Use of the alternate coal had no impact on outfall discharges; all NPDES compliance reports for the test period are on file and available at the Massachusetts DEP.

Brayton Point currently conducts an extensive ground water monitoring program. Massachusetts DEP requires the monitoring of wells associated with the ash disposal and plant impoundments. Samples collected quarterly are analyzed for the following parameters: pH, temperature, alkalinity, conductivity, total dissolved solids, chlorides, sulfates, dissolved iron and dissolved manganese. In addition, annual samples are analyzed for the following dissolved parameters: aluminum, arsenic, barium, cadmium, calcium, chromium, copper, lead, mercury, selenium, silver, sodium, zinc, and organic carbon. No compliance monitoring of solid waste or by-product streams is required; however, the permit for the Brayton Point coal ash landfill requires that a daily record of the volume of the ash sent to the ash landfill be maintained. Use of the alternate coal had no impact on groundwater measurements or the coal ash landfill; all groundwater and landfill reports for the test period are on file and available at NEP and the Massachusetts DEP.

Table 5-7
Environmental Source Monitoring Requirements for New England Power's Brayton Point Unit 3

Stream	Location	Parameter	Frequency	Monitoring**
Gaseous	In Stack	Opacity	Continuous	C
		SO_2	Continuous	C
		SO_3	1/Test	S
		NO_x	1/Test	S
		O_2	1/Test	S
		Particulates	1/Test	S
		Particle Size	1/Test	S
	Coal Analysis	SO_2	1/Shipment	C
	Boiler Exit	SO_2	1/Test	S
		SO_3	1/Test	S
		NO_x	1/Test	S
		CO	1/Test	S
		O_2	Continuous	S
	ESP Inlet	SO_3	1/Test	S
		NO_x	1/Test	S
		Particulates	1/Test	S
		Particle Size	1/Test	S
		Fly Ash Resistivity	1/Test	S
	ESP Outlet	Particulates	1/Test	S
Aqueous	Outfall 001	Flow	Continuous	C
		Temperature	Continuous	C
		Temperature Change	Continuous	C
		Total Residual Organics	1/Day	C
	Outfall 004A	Flow	Continuous	C
		Total Suspended Solids	1/Week	C
		Oil & Grease	1/Week	C
		Copper, Nickel, Iron, Zinc	1/Week	C
	Outfall 004B	Flow	Continuous	C
		Total Suspended Solids	1/Day	C
		Oil & Grease	1/Day	C
		Copper, Nickel, Iron, Zinc	1/Day	C
	Outfall 005*	Flow	Continuous	C
		Temperature	Continuous	C
	Outfall 009, 010,	Oil & Grease	1/Month	C
	Outfall 017	Flow	Continuous	C
	Outfall 018*	Flow	Continuous	C
	Outfall 020	Flow	Continuous	C

* Not in service
** C = Compliance S = Supplemental

Table 5-8
Environmental Source Monitoring Requirements for New England Power's Brayton Point Unit 2 (Continued)

Stream	Location	Parameter	Frequency	Monitoring**
Solid				
Feed Coal	Feed Inlet	Proximate Analysis	2/Day	S
		Ultimate Analysis	2/Day	S
		Calorific	2/Day	S
		Mineral Ash	2/Day	S
		Ash Fusion	2/Day	S
		Grindability	2/Day	S
	Coal Flow Integrators	Mass Flow	1/Hour	S
Bottom Ash	Bottom Ash Hopper	Carbon Content	1/Test	S
		Sulfur Content	1/Test	S
Fly Ash	Fly Ash Hopper	Carbon Content	1/Test	S
		Sulfur Content	1/Test	S

* Not in Service
** C = Continuous / S = Supplemental

The NPDES permit for Brayton Point Station (Permit No. MA0003654) specifies 11 outfalls that discharge to a natural receiving water. Table 5-8 lists the specific outfalls, measured parameters, and monitoring frequency. These outfalls are analyzed for flow rate, intake and discharge temperatures, total residual organics, total suspended solids, oil and grease, and the metals: copper, iron, nickel, and zinc. Use of the alternate coal had no impact on outfall discharges; all NPDES compliance reports for the test period are on file and available at NEP and the Massachusetts DEP.

Brayton Point currently conducts an extensive ground water monitoring program. Massachusetts DEP requires the monitoring of wells associated with the ash disposal and plant impoundments. Samples collected quarterly are analyzed for the following parameters: pH, temperature, alkalinity, conductivity, total dissolved solids, chlorides, sulfates, dissolved iron and dissolved manganese. In addition, annual samples are analyzed for the following dissolved parameters: aluminum, arsenic, barium, cadmium, calcium, chromium, copper, lead, mercury, selenium, silver, sodium, zinc, and organic carbon. No compliance monitoring of solid waste or by-product streams is required, however the permit for the Brayton Point coal ash landfill requires that a daily record of the volume of the ash sent to the ash landfill be maintained. Use of the alternate coal had no impact on groundwater measurements or the coal ash landfill; all groundwater and landfill reports for the test period are on file and available at NEP and the Massachusetts DEP.

6.0

COMMERCIALIZATION POTENTIAL AND PLANS

Commercialization is a significant focus of the Clean Coal Technology program and of the CQE project. A market analysis, including a discussion of potential customers and market barriers, and a commercialization plan, which discusses potential licensing arrangements, has been prepared.

6.1 Market Analysis

An analysis of the market for CQE shows that the most likely customers for CQE are power generation organizations, fuel suppliers, environmental organizations, government organizations, and engineering firms. These world-wide organizations can take advantage of CQE's capability to evaluate the impact of fuel quality on entire generating systems.

6.1.1 Applicability of the Technology

CQE is a versatile program for conducting evaluations of the effects of fuel selection decisions on utility-wide performance and economics. As such, it is a useful tool for organizations that require a way of assessing the overall impacts of changes in fuel or plant equipment on the performance and costs of utility systems. CQE is unique in that it can bring together in a systematic framework the large number of interrelated effects that a change to either the plant fuel, load curve, equipment, or environmental constraints have on the total utility system.

Because CQE has such breadth in its considerations, the potential uses of the program, and hence the opportunities for commercialization are widespread. CQE can be used by, and hence can be marketed to, a wide-ranging variety of companies that are involved in power generation, or are direct or indirect suppliers to the power generation industry. In addition, every effort was made during development of CQE to either incorporate or allow for the incorporation of features that would promote its marketability on a world-wide basis. These features include the use of international monetary and unit measurement systems.

The organizations that are the most likely customers of CQE and CQE related services are:

- Power Generation Organizations. These include public utilities in the traditional sense, but in addition, a growing number of independent power generation organizations both domestically and abroad. These organizations will use CQE for the following purposes:

Fuel evaluations. One of the largest uses of CQE will continue to be the kinds of evaluations that previously had been done with CQE's predecessor, CQIM. These evaluations are assessment of the effects that a change in coal quality will have on power plant performance and economics. CQE has a number of distinct advantages, however, in performing these evaluations, specifically its use of far more sophisticated slagging and fouling predictive methods and its ability to store and retrieve prior results.

Plant Equipment Evaluations. CQE, in contrast to CQIM or any other program of this type, has the ability to replace a single power plant component with a model of an alternative plant component. This ability allows the user to evaluate a change to the plant configuration that would allow the burning of a fuel that otherwise would cause a plant de-rate. In addition, CQE can use existing results for the rest of the plant, thus allowing the user to only run the change-affected sections of the model. This capability speeds execution time greatly.

Environmental Evaluations. CQE allows the user to assess the effect that a change either in fuel or power plant equipment has on the power generation organization's overall environmental compliance situation. In general, this capability is peculiar to the United States, in that it is the only country with an emissions trading scheme. Other countries still rely heavily on the single-source-limit type of environmental constraint. CQE can certainly do these type of evaluations as well, but the allowance trading feature will not be a strong selling feature internationally.

Litigation Support. CQE can be used by power generation organizations to assess the magnitude of damages in cases where fuel quality or equipment performance issues result in litigation. CQIM has been used for these purposes in the past, and CQE will undoubtedly be used for this purpose in the future.

- Fuel Suppliers. CQE can be used by fuel suppliers in support of market strategy, customer support, and litigation support.

Market Strategy. CQE is applicable to fuel suppliers in cases where evaluations of their fuels for potential customers is desired. CQE can be used in estimating the cost that a potential customer should be willing to pay for the fuel, any likely impacts of the fuel on power plant equipment that may eliminate their fuel from consideration, or the relative ranking of their fuel vis-a-vis their competitors fuels. In addition, because many utilities will use CQE to evaluate potential coal bids, it provides the supplier with insight into the selection process.

Customer Support. CQE can serve as a means of diagnosing performance issues with a given fuel. The model will allow suppliers to estimate the actual impact that coal properties have on a particular piece of equipment, as well as arrive at potential solutions to the problem.

Litigation Support. CQE can be used by fuel suppliers to assess the magnitude of damages in cases where fuel quality or equipment performance issues result in litigation. CQIM has been used for these purposes in the past, and CQE will undoubtedly be used for this purpose in the future. In these cases, the data needed to develop site-specific models of CQE are available through discovery.

- Environmental Organizations. CQE can be used by environmental organizations for evaluating the effects of changes in fuel supply or power plant equipment on the environmental compliance capabilities and costs of a single plant or an entire utility system.

- Government Organizations. In the United States and other countries where power is generated by private corporations, government generally assumes a regulatory role. In these instances, CQE can be used for evaluating environmental performance, fuel purchase decisions, and as a general cross-check on costs that are ultimately passed on to the customers. Particularly in states where fuel adjustment clauses are used, public utility commissions could use CQE for monitoring fuel consumption and costs.

  CQE can also be used by the Department of Energy for comparing alternate technologies for cleaning and using coal, alternate environmental compliance strategies, and for planning new research and development efforts. In addition, the use of CQE by DOE helps promote the use of this and other Clean Coal Technology Program products both domestically and overseas.

  Overseas, governments are frequently the entities that actually generate electricity. In these instances, the use by government organizations becomes more like that of other power generation organizations.

- Engineering Firms. Engineering and equipment supplies firms can use CQE in two roles, one as a conventional user, assessing the impacts of fuels on power plant equipment and costs, or re-sizing equipment for new fuels, and one as a consultant, performing similar studies for other organization using CQE.

6.1.2 Market Size

CQE has three products that result in recoupment to DOE: use licenses, consultant licenses, and commercialization licenses. Each product has its own particular market.

6.1.2.1 Use Licenses. The largest market for use licenses (in fact the largest CQE market in all) is power generation organizations. Worldwide, the number of utilities in each country that have coal-fired capacity and the number of coal-fired power plants in each country are listed in Table 6-1. In ranking each country by likelihood for CQE sales, two factors weigh against each other: First, CQE is most likely going to be purchased by a power generation organization for its entire system, therefore, those countries with a large number of power generation organizations have the potential of higher sales. On the other hand, those power generation

Table 6-1
Utilities and Power Plants World-Wide

Country	Utilities	Coal-Fired Plants	P/U Index	Cumulative Utilities
Poland*	1	22	22.00	1
CIS (former USSR)*	1	21	21.00	2
China*	4	82	20.50	6
South Africa	1	20	20.00	7
Turkey	1	19	19.00	8
Italy	1	17	17.00	9
Romania*	1	15	15.00	10
Czechoslovakia*	1	13	13.00	11
Indonesia	1	13	13.00	12
France	2	20	10.00	14
Denmark	2	20	10.00	16
Korea, South	1	10	10.00	17
United Kingdom	4	40	10.00	21
Philippines	1	9	9.00	22
Greece	1	9	9.00	23
Hungary*	1	8	8.00	24
India	11	78	7.09	35
Ireland	1	7	7.00	36
Mexico	1	7	7.00	37
Bulgaria	1	7	7.00	38
Thailand	1	6	6.00	39
Taiwan	1	6	6.00	40
Australia	5	29	5.80	45
Brazil	2	10	5.00	47
Egypt	1	5	5.00	48
Canada	8	33	4.13	56

Table 6-1
Utilities and Power Plants World-Wide (continued)

Country	Utilities	Coal-Fired Plants	P/U Index	Cumulative Utilities
New Zealand	1	4	4.00	57
Morocco	1	4	4.00	58
Belgium	5	16	3.20	63
Israel	1	3	3.00	64
Pakistan	1	3	3.00	65
Portugal	1	3	3.00	66
Japan	14	37	2.64	80
United States (less EPRI)	61	146	2.39	141
Germany	59	128	2.17	200
Austria	6	12	2.00	206
Botswana	1	2	2.00	207
Chile	3	6	2.00	210
Dominican Republic	1	2	2.00	211
Hong Kong	2	4	2.00	213
Finland	14	23	1.64	227
The Netherlands	4	6	1.50	231
Spain	16	24	1.50	247
Sweden	13	14	1.08	260
Argentina	2	2	1.00	262
Sri Lanka	1	1	1.00	263
Colombia	3	3	1.00	266
Malaysia	1	1	1.00	267

**The breakup of former state-controlled power authorities in these countries may increase the likelihood* of CQE sales.

organizations that have a single plant have less incentive to invest in the purchase of CQE.

Because CQE can perform evaluations on a system-wide basis, large power generation organizations will tend to purchase a single CQE with a license for large numbers of multiple users. Power generation organizations with a single power plant, however, will probably purchase a three-user copy of CQE (the minimum configuration). Because the incremental cost of a multiple user license is small compared to the initial cost of the three-user CQE, the trend toward small independent power producers both domestically and internationally (particularly in the former eastern-block countries) bodes well for sales of CQE.

The other organizations that are listed as potential users of CQE in section 6.1.1 are not as likely to be purchasers of the software as they are to be purchasers of CQE consulting services for two reasons: first, their use is not likely to be as frequent as the use by power generation organizations, and hence they are not as likely to invest in the program and in developing the expertise to run the program; and second, they are less likely to have access to the detailed data required to develop accurate site-specific case studies under CQE.

6.1.2.2 Consultant Licenses. The most likely purchasers of consultants licenses are the large architect/engineering firms, and boiler manufacturers. In all, there are probably one hundred large engineering firms worldwide, and twenty boiler manufacturers. Table 6-2 is a partial list of these types of organizations.

6.1.2.3 Commercialization Licenses. The same organizations that are the most likely candidates for consultants licenses are the most likely candidates for commercialization licenses. There are two types of commercialization licenses, regional commercialization licenses and world-wide commercialization licenses.

6.1.3 Market Barriers

Market barriers to CQE commercialization include: the EPRI membership and utility-owned engineering firms receiving CQE as part of their EPRI dues, a high purchase price, continued CQIM sales, competition from in-house programs, a language barrier, and lack of foreign boiler models.

6.1.3.1 EPRI Membership. EPRI members receive CQE pre-paid as part of their EPRI dues. Approximately seventy percent of the public utilities in the United States are members of EPRI and therefore would not purchase CQE. EPRI membership limits sales of CQE use and consulting licenses in two additional ways, however. First, EPRI is actively pursuing membership of foreign utilities as "affiliate members". Some of these affiliate members have rights to products of the EPRI Fossil Generation business unit, and therefore would not purchase CQE. As EPRI continues to pursue these affiliate members, the existing foreign market for CQE could be eroded.

Second, EPRI's use license with their U.S. members allows the license-holder to contract with another organization to run their copy of CQE. Because EPRI member utilities are such a large share of the domestic market for CQE services, engineering firms who would otherwise purchase a consultants license may not elect to purchase the license and use an EPRI member's license. In addition, this represents a software security problem if all copies of CQE acquired by the engineering firm by this method are not returned to the member utility.

Table 6-2
Major International Engineering Firms and Boiler Manufacturers

ABB and ABB Combustion Engineering	Zurn Industries
Stone & Webster	C.S. Sirrine
Ebasco	Burns & Roe
Bechtel	Burns & McDonnell
Gilbert Commonwealth	Pope, Evans & Robbins
Sargent & Lundy	AMCA Engineers & Constructors
Fluor Daniel	Raytheon
ICF Kaiser	ABCO
Stearns	Tampella Power
Bharat Heavy Electricals, Ltd.	ENRON
Deutsche Babcock (Riley Stoker)	Rheinbraun
Foster Wheeler	Duke
Nooter Erikson	Soderenergi AB
Brown & Root	Brown & Cladwell
Sverdrup	VEBA Kraftwerk Ruhr AG
Ford, Bacon & Davis	RWE AG
Ahlstrom	Siemens
Mitsubishi	United Engineers & Constructors
Wheelabrator Frye	Black & Veatch

6.1.3.2 Utility-Owned Engineering Firms. At least two utilities, Duke and Southern Company, are diversifying into providing engineering services, and constructing and owning (in part or wholly) power plants internationally. These companies are also EPRI member utilities and will get CQE as part of their dues. It is unclear if the current EPRI software license prohibits their use of CQE as a consulting tool in projects of this nature, or that EPRI will choose to pursue revoking their licenses if they do.

6.1.3.3 Perceived High Purchase Price. Presently, CQE is expected to sell for $100,000. Many organizations (particularly internationally) will believe they do not have the resources to purchase software that is perceived to be expensive. However, CQE can easily pay for itself in a single, positive use.

6.1.3.4 Continued CQIM Sales. Black & Veatch will continue to sell CQIM after the release of CQE. Because CQE and CQIM are similar products, and some of the evaluations that would be performed using CQE could be performed using a combination of CQIM and other products, continued sale of CQIM will compete for sales of CQE. In addition, Black & Veatch currently realizes more from the sale of a CQIM license than they will from the sale of a CQE license. Therefore, there is a financial incentive for them to continue selling CQIM. Black & Veatch recently invested their own funds to convert CQIM to use SI units. This version of CQIM is called CQIM International. Black & Veatch plans to market CQIM International overseas.

6.1.3.5 In-house Programs. Some organizations (utilities, coal companies, and engineering firms) have developed in-house programs to do evaluations similar to CQE. Some examples are:

CQEA. A program developed by New York State Electric and Gas (NYSEG) that purports to perform analyses similar to CQIM. CQEA was developed specifically for NYSEG units, based on their experience with the coals that they purchase, although they have been attempting to generalize the program to other units. This program has just recently been converted to a PC version by Black & Veatch.

A version of CQIM with an in-house boiler model was developed by Black & Veatch for National Power in England.

6.1.3.6 Language. Currently, CQE is only available in English. CQE does allow SI units. The structure of CQE allows for relatively easy conversion to foreign languages, however, these foreign language dictionaries do not currently exist.

6.1.3.7 Foreign Boilers. CQE currently does not have some commonly encountered foreign boiler designs, such as the tower boiler or the Benson boiler. Black & Veatch does have a model of this type of boiler that was developed for ESKOM in South Africa, but that model is not yet incorporated into CQE.

6.1.4 Significance of Market Barriers

Figure 6-1 shows the estimated significance of the above market barriers.

Plans to mitigate these barriers include:

- High Purchase Price. A number of creative financing plans have been discussed, including lease-to-buy, extended payment, and pay-by-usage options. The price for CQE must, of course, be continually re-assessed in light of the program's functionality, as well as sales, market acceptance, and competition.

- EPRI Membership. There is very little that either CQ Inc. or B&V can do to mitigate this barrier. The only potential for mitigating this barrier is to rapidly disseminate CQE internationally so that potential customers will have already purchased CQE before considering joining EPRI.

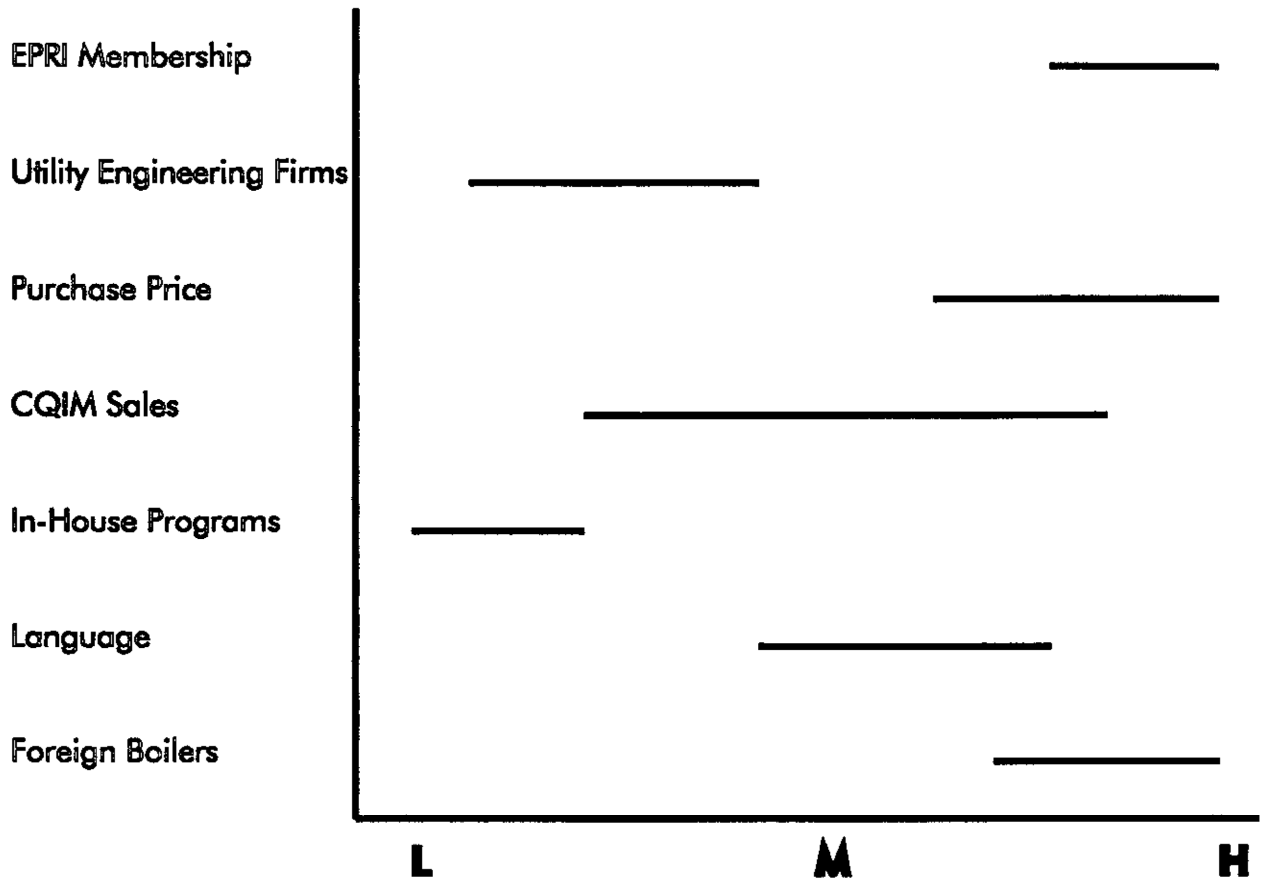


Figure 6-1
Significance of Market Barriers

- Continued CQIM Sales. This barrier can be managed by managing the demand for CQIM. If CQE is couched as the superior product (which it is), and the price reflects the incremental benefit to the customer of using CQE, demand for CQIM, and hence sales of CQIM will decrease.

- Utility Engineering Firms. Discussions are already underway with EPRI to amend the general software license to specifically prohibit the use of CQE in consulting situations.

- Foreign Boilers. EPRI currently has a model of the tower boiler that was developed for ESKOM in South Africa, but has not made the decision to allow the model to be incorporated into CQE.

6.2 Commercialization Plans

The focus for commercialization will be in the sale of use licenses, consultant licenses, regional commercialization licenses, and world-wide commercialization licenses.

6.2.1 Use Licenses

Use licenses will constitute the largest sales of CQE. Because CQE can be installed and run on a local area network (LAN), more than one person or organizational unit within a company is able to run CQE simultaneously. In fact, this is an important feature of the software, because it provides consistency in the data used within an organization. However, whereas it was not unusual for a CQIM license holder to purchase multiple copies of CQIM, companies will probably not purchase multiple copies of CQE. The introductory price for CQE is $100,000.

Consultation licenses will be priced at the same initial cost as a use license, but will require additional use royalties for each consulting period. A consultation license includes a use license.

Regional commercialization licenses will cost 2.5 times the cost of use license and will include a consultation license and use license.

World-wide commercialization licenses will cost five times the cost of a use license and will include a consultation license and use license.

CQ Inc. plans to service North America directly by marketing use licenses and consulting licenses in the United States and Canada. We feel that for an organization with the size and resources that CQ Inc. currently have, the US and Canada are as large a market as we can realistically market, sell, and service.

CQ Inc. plans to market CQE using the following vehicles:

- Technical papers
- Magazine articles
- Magazine advertisements
- Direct contact (telephone)
- Internet (www.fuels.bv.com)
- Trade show demonstrations

CQ Inc. will focus its marketing effort on utilities that are not EPRI members and the larger coal companies (Consol, Exxon, Cyprus/AMAX) for use licenses.

6.2.2 Consultant Licenses

CQ Inc. will focus on foreign-based engineering companies, and U.S.-based engineering companies with large amounts of foreign work for candidates for consultants licenses. U.S.-based engineering companies with predominantly domestic contracts will not be neglected, but because they can use a client's copy of CQE so easily, they will be less inclined to purchase such a license.

6.2.3 Regional Commercializers

CQ Inc. plans to team with major engineering firms as regional commercializers in the following regions:

- South America
- Southeast Asia, China and Japan
- India
- Europe (including CIS)
- Africa

Because of the cost of a regional commercialization license, the area that is defined as a "region" must be large enough for the commercializer to recoup their investment.

Using regional commercializers is probably the best choice for marketing the software world-wide, because:

- A regional commercializer is more aware of the potential customers and their cultural differences in a given region, thus facilitating sales.

- Travel within a region is less costly, hence the commercializer is more likely to make more frequent customer contact.

- Time zones differences between customer and commercializer are smaller, thus improving the response time on product support.

CQ Inc. will focus on the non-US-based engineering companies in Table 6-2 for regional commercializer licenses.

6.2.4 World-wide Commercializers

CQ Inc. will grant worldwide commercializer status if asked. CQ Inc. has a world-wide commercialization license, and has already granted another world-wide commercialization agreement to Black & Veatch. We have no plans to pursue a third world-wide commercializer, although if an organization such as a regional commercializer requests one, we will seriously consider their request.

7.0

CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations from this report show that CQE will benefit coal-fired power plants in their commitments to produce energy economically and with concern for the environment.

7.1 Conclusions

The following conclusions are made regarding the development of CQE and its value to utilities.

- Laboratory- and full-scale tests measured the effectiveness of physical cleaning in removing ash-forming minerals, pyritic sulfur, and trace elements from bituminous and subbituminous coals. All of these impurities can be removed from the thirteen test coals with differing levels of efficiency.

- Laboratory- and pilot-scale combustion tests assessed the potential performance improvements at power plants that could burn higher quality clean coals derived from the same run-of-mine feedstock as their present fuel. Full-scale power plant tests demonstrated the effects of both fuel quality and operating practices on combustion performance and emissions. Environmental monitoring at all test sites showed no adverse environmental impacts from this project.

- Acid Rain Advisor software was designed as part of the CQE project to assist users in managing Clean Air Act compliance evaluations, either within CQE or as a stand-alone program.

- Electric utilities, both domestic and international, now have a tool to evaluate the system-wide consequences of fuel purchase decisions on power plant performance, emissions, and power generation costs. The software can examine potential changes in coal quality, transportation options, pulverizer performance, boiler slagging and fouling, emissions control alternatives, and byproduct disposal for pulverized-coal and cyclone-fired power plants. New boiler slagging and fouling models, based on CCSEM laboratory analyses, can operate in CQE as long as a user has less-expensive proximate data. As a network-aware application, CQE can be maintained by one user in an organization and used by others in the organization to ensure that all data and conclusions are consistent throughout the organization. These new capabilities make CQE the preeminent software for performing fuel purchase decisions, plant improvement evaluations, and system-wide compliance strategy development.

- Commercialization plans call for organizations (initially CQ Inc. and Black & Veatch) to:
    - Provide consulting services using CQE
    - Issue use licenses to others
    - Issue regional commercialization licenses

7.2 Recommendations

The following recommendations are made regarding the use of CQE and its future development.

- CQE, as developed under this cooperative effort, will be a valuable tool for utilities and coal producers worldwide. Further refinement and updating is warranted as new predictive models are refined and validated. Future development of CQE should include coal gasification, fluidized bed boilers, European and Asian boiler designs, and post-combustion SO_2 and NO_x controls technologies.

- To facilitate the adoption of other Clean Coal Technologies by electric generation companies, the results of DOE-sponsored Clean Coal Technology demonstrations should be summarized in a consistent format to facilitate their future inclusion in CQE. This would allow power generating companies to evaluate new technology in a familiar and easy-to-use framework.

- Initial uses of CQE should be documented in case histories to accelerate market penetration.

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Conference: The Effects of Coal Quality on Power Plants (EPRI)

7
Date: August 25-27, 1992
Author(s): S. Lowe and P. Vitta of Southern Company Services and R. Cromwell and M. Matson of Mississippi Power Company
Title: Assessment and Validation of Coal Quality Impact Model at Mississippi Power Company's Unit 4
Conference: The Effects of Coal Quality on Power Plants (EPRI)

8
Date: August 25-27, 1992
Author(s): S. Benson, S. Allen, and C. Zygarlicke of UND's Energy and Environmental Research Center, R. Borio of ABB/CE, and A. Mehta of EPRI
Title: A Comparison of Ash Deposition Behavior in Field, Pilot, and Bench-Scale Testing
Conference: The Effects of Coal Quality on Power Plants (EPRI)

9
Date: August 25-27, 1992
Author(s): R. Thompson (Fossil Energy Research Company), Z. Frompovicz (EER), E. Landham (Southern Research Institute), P. Vitta (Southern Companies Services), and D. Giovanni (Electric Power Technologies)
Title: Measuring the Impact of Coal Quality on Boiler Operation and Performance
Conference: The Effects of Coal Quality on Power Plants (EPRI)

10
Date: August 25-27, 1992
Author(s): P. Vitta (SCS), Z. Frompovicz (EER), R. Cromwell (MPC), and M. Matson (MPC)
Title: Coal Quality Field Test at Mississippi Power Company's Watson Unit 4
Conference: The Effects of Coal Quality on Power Plants (EPRI)

11	
Date:	September 22-24, 1992
Author(s):	C. Harrison (CQ Inc.) and R. Evans (DOE)
Title:	Coal Quality Expert: Status and Software Specifications
Conference:	First Annual Clean Coal Technology Conference
12	
Date:	October 1992
Author(s):	G.A. Clark, J.L. Lyden, W.F. Musiol (Babcock & Wilcox Co.); R. J. Evans (DOE), Z.G. Frompovicz (Energy and Environmental Research Corp.), and C. Raleigh (CQ Inc.)
Title:	Assessment of the Impact of Cleaned Coals on Utility Boiler Performance
Conference:	ASME Joint Power Generation Conference, Atlanta, GA
13	
Date:	November 17-19, 1992
Author(s):	Scott Stallard, John Pavlish, Brad Gellerstedt (B&V)
Title:	The Coal Quality Expert: Designing for Maximum Flexibility
Conference:	Power-Gen '92, Orlando, FL
14	
Date:	March 1993
Author(s):	T.A. Erickson, S.E. Allan, D.P McCollor, J.P. Hurley (EERC); S, Srinivasachar, S.G. Kang, J.E. Baker, M.E. Morgan, S.A. Johnson (PSI Technology Co.); R. Borio (ABB Combustion Engineering)
Title:	Modelling of Fouling and Slagging in Coal-Fired Utility Boilers
Conference:	ACERC Meeting, Utah (BYU University)
15	
Date:	April 26-29, 1993
Author(s):	Clark D. Harrison (CQ), G. Scott Stallard (B&V), and Dave O'Connor (EPRI)
Title:	Coal Quality Expert: A Powerful New Tool for Coal Burning Utilities To Reduce Emissions and Cost
Conference:	18th International Technical Conference on Coal Utilization & Fuel Systems, Clearwater, FL

16	
Date:	September 7-9, 1993
Author(s):	R.L. Patel of ABB Combustion Engineering, M.E. Morgan and S.G. Kang of PSI PowerServe, and T.A. Erickson and S.E. Allan of the UND-EERC (presented by Dick Borio of ABB CE)
Title:	The Coal Quality Expert: A Focus on Slagging and Fouling
Conference:	Second Annual CCT Conference, Atlanta, GA

17	
Date:	November 30-December 3, 1993
Author(s):	Scott Stallard (B&V) and Dave O'Connor (EPRI)
Title:	CQE: Bringing New Dimensions to Fuel Decisions
Conference:	IEA 2nd International Conference on the Clean and Efficient Use of Coal and Lignite: Its Role in Energy, Environment, and Life, Hong Kong

18	
Date:	September 6-8, 1994
Author(s):	Dave O'Connor (EPRI) and Scott Stallard (B&V)
Title:	The CQE Project: Producing Innovative Software for Economical Deployment of Coal Technologies
Conference:	Third Annual CCT Conference, Chicago, IL

Pilot-Scale Combustion Reports

1	
Date:	July 1992
Prepared by:	ABB Combustion Engineering, Inc.
Title:	Developing a Coal Quality Expert: Combustion and Fireside Performance Characterization Factors. Topical Report on Coals from Public Service of Oklahoma's Northeastern Station.
2	
Date:	September 1992
Prepared by:	Babcock & Wilcox
Title:	Assessment of the Impact of Cleaned Coal on Boiler Performance
3	
Date:	April 1993
Prepared by:	ABB Combustion Engineering, Inc.
Title:	Developing a Coal Quality Expert: Combustion and Fireside Performance Characterization Factors. Topical Report on Coals from Mississippi Power's Watson Station.

Utility Boiler Field Test Reports

1	
Date:	January 1993
Prepared by:	Electric Power Technologies, Inc.
Title:	Coal Quality Field Test at Mississippi Power Company's Watson Unit No. 4.
2	
Date:	October 1995
Prepared by:	Electric Power Technologies, Inc.
Title:	Coal Quality Field Test at Northeastern Unit 4 of Public Service Company of Oklahoma.

Environmental Monitoring Reports

1
Date: January 1993
Title: Environmental Monitoring Report Test Series No. 1 - Public Service Company of Oklahoma Northeastern Unit No. 4

2
Date: October 1993
Title: Environmental Monitoring Report Test Series No. 2 - Mississippi Power Company Watson Unit No. 4

3
Date: December 1994
Title: Environmental Monitoring Report Test Series No. 3 - Northern States Power Company King Station Unit No. 1

4
Date: December 1994
Title: Environmental Monitoring Report Test Series No. 4 - Southern Company Services/Alabama Power Company Gaston Station Unit No. 5

5
Date: April 1995
Title: Environmental Monitoring Report Test Series No. 5 - New England Power Service Company Brayton Point Station Unit No. 3

6
Date: April 1995
Title: Environmental Monitoring Report Test Series No. 6 - New England Power Service Company Brayton Point Station Unit No. 2

Coal Characterization Reports

1

Date:	July 1991
Prepared by:	R. L. Dospoy (CQ Inc.) for EPRI and DOE
Title:	Coal Cleanability Characterization of Croweburg Seam Coal

2

Date:	February 1992
Prepared by:	D. E. McCollough (CQ Inc.) for EPRI and DOE
Title:	Coal Characterization of West Kentucky No. 11 Seam Coal

3

Date:	July 1992
Prepared by:	D. E. McCollough (CQ Inc.) for EPRI and DOE
Title:	Coal Characterization of Illinois No. 2, No. 3, and No. 5 Seam Coals

4

Date:	August 1992
Prepared by:	R. L. Dospoy (CQ Inc.) for EPRI and DOE
Title:	Coal Cleanability Characterization of Pratt and Utley Seam Coals

5

Date:	June 1993
Prepared by:	C. E. Raleigh and R. L. Dospoy (CQ Inc.) for EPRI and DOE
Title:	Characterization and Evaluation of the Cleanability of Subbituminous Coals from the Powder River Basin

Miscellaneous

Date:	October 1993
Prepared by:	PSI PowerServe
Title:	Coal Quality Expert Final Report